COMPLEX ADAPTIVE SYSTEMS SIMULATION-OPTIMIZATION FRAMEWORK FOR ADAPTIVE URBAN WATER RESOURCES MANAGEMENT

A Dissertation

by

MARCIO HOFHEINZ GIACOMONI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2012

Major Subject: Civil Engineering

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ABSTRACT

Complex Adaptive Systems Simulation-Optimization Framework for Adaptive Urban Water Resources Management. (August 2012)

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Co-Chairs of Advisory Committee: Dr. Emily M. Zechman
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Population growth, urbanization and climate change threaten urban water systems. The rise of demands caused by growing urban areas and the potential decrease of water availability caused by the increase of frequency and severity of droughts challenge the continued well-being of society. Due to increasing environmental and financial constraints, water management paradigms have shifted from supply augmentation to demand management, and water conservation initiatives may efficiently decrease water demands to more sustainable levels. To provide reliable assessment of the efficiencies of different demand management strategies, new modeling techniques are needed that can simulate decentralized decisions of consumers and their interactions with the water system. An integrated simulation-optimization framework, based on the paradigm of Complex Adaptive Systems, is developed here to model dynamic interactions and adaptations within social, built, and natural components of urban water systems. The framework goes beyond tradition engineering simulations by incorporating decentralized, heterogeneous and autonomous agents, and by simulating dynamic feedback loops among modeling components. The framework uses modeling techniques including System Dynamics, Cellular Automata, and Agent-based Modeling to simulate housing and population growth, a land use change, residential water consumption, the hydrologic cycle, reservoir operation, and a policy/decision maker. This research demonstrates the applicability of the proposed framework through a series of studies applied to a water supply system of a large metropolitan region that is located in a semi-arid region and suffers recurrently from severe droughts. A set of adaptive demand management strategies, that apply contingency restrictions, land use planning, and water conservation technologies, such as rainwater harvesting systems, are evaluated. A multi-objective Evolutionary Algorithm is coupled with the CAS simulation framework to identify optimal strategies and explore conflicting objectives within a water system. The results demonstrate the benefits of adaptive management by updating management decisions to changing conditions. This research develops a new hydrologic sustainability metric, developed to quantify the stormwater impacts of urbanization. The Hydrologic Footprint Residence captures temporal and spatial hydrologic characteristics of a flood wave passing through a stream segment and is used to assess stormwater management scenarios, including Best Management Practices and Low Impact Development.

DEDICATION

This Dissertation is dedicated to my parents, James and Maria Eunice Giacomoni for all the love and support. It is also dedicated to my future wife Laura Joost Giacomoni, to my sisters Claudia and Elise, and my brother Bruno.

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NOMENCLATURE

BMP	Best Management Practice
CAS	Complex Adaptive Systems
CA	Cellular Automata
EA	Evolutionary Algorithm
HEC-RAS	Hydrologic Engineering Center River Analysis System
HFR	Hydrologic Footprint Residence
HRU	Hydrologic Response Unit
LID	Low Impact Development
SWAT	Soil and Water Assessment Tool
TCEQ	Texas Commission on Environmental Quality
TRA	Trinity River Authority
TRWD	Tarrant Regional Water District
TWDB	Texas Water Development Board

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CHAPTER I

INTRODUCTION

Urban water resource systems are complex and dynamic because multiple interactions and feedbacks exist among natural, built, and social components. Water supplies and demands within a water system result from temporal and spatial processes such as climatic variability, regulatory ordinances, consumer preferences, and economic factors. Computer models, built to represent water systems, are used to simulate water demands and supplies for aiding watershed management. Typical modeling approaches, however, incorporate demand-side and supply-side components separately, ignoring feedbacks and adaptations that occur within a water system. For example, water resource plans project future demands based on population growth predictions and average per capita water use and compare them to existing supplies. If future demands surpass existing supplies, supply augmentation projects may be proposed. The supply-side management paradigm alone, however, is not able to solve water resource challenges, as water systems, especially in urban areas, are becoming more constrained by increasing demands caused by population growth. Moreover, climate change tends to increase the variability of the hydrologic cycle, increasing the uncertainty of future water supplies. As the complexity of water resource management increases due to environmental constraints and future uncertainties, a management that allows adaptation in response to the change of the system can improve water resource sustainability.

This dissertation follows the style of *Journal of Hydrologic Engineering*.

Adaptive demand management is able to increase system flexibility, to more efficiently address increasing stresses, such as droughts. Modeling adaptive demand management requires new modeling paradigms that simulate dynamic adaptations between demand-side and supply-side components, and the development of these tools can advise improved management of water resources.

The primary objective this research is the development of an integrative simulation-optimization framework to simulate an urban water system as Complex Adaptive System (CAS). A CAS is characterized as networks of interacting components that influence emergent system properties through dynamic feedback (Axelrod 1997; Holland 1995; Miller and Page 2007). The new framework interconnects modeling components that represent population growth, land use change, the hydrologic cycle, residential water consumption, water infrastructure, and policy/decision rules through the use of modeling techniques such as system dynamics (Forrester 1961), cellular automata (Wolfram 1983), and agent-based modeling (Holland 1995). The CAS modeling framework provides simulation above traditional engineering simulation through the consideration of heterogeneous decentralized components and feedback loops.

In the decentralized modeling paradigm, a bottom-up approach is used where the behavior of autonomous units, represented by agents within a network or cells within a grid, is simulated as it influences both the supply and demand of water. To simulate the influence of behaviors on water supply, a hydrologic model is coupled with a cellular automata land use change model to represent the hydrologic variability and how it is affected by the sprawl of urban areas. A regular grid of cells is used to represent the land use, which changes over time as a result of decentralized local interactions among cells. The change of land use from natural to urban can alter the hydrologic flow regime in the long term, which can directly impact the watershed yields for water supply. Individual behaviors also affect demands, and these impacts are simulated through a residential consumer agent-based model that computes the indoor and outdoor water consumption of households based on heterogeneous characteristics, such as the size of a household, lot size, and roof size. The consumer agent-based model simulates individual and decentralized decisions about water consumption that collectively define the total demand.

The CAS framework is designed as a set of modeling components that are dynamically interrelated. Each model generates outputs that are used as inputs to other components, interconnecting processes and generating feedback loops. For example, at each time step, the policy maker agent-based model receives storage information from the reservoir component, and if the level of the reservoir is lower than a certain trigger, water conservation measurements, such as outdoor water use restrictions, are enacted. This information is sent to the residential consumer agent-based model that adjusts households' behaviors and computes water consumptions. The reduction of the households' consumption impacts the reservoir storage as less water is withdrawn, helping the system to recover and alleviate the water conservation measures faster. The dynamic nature of the CAS framework allows the assessment of adaptive water management strategies such as water conservation programs, drought plans, land use policies, and others.

The CAS modeling framework is coupled with a Multi-Objective Evolutionary Algorithm (MOEA) (Deb et al. 2002) designed to identify tradeoffs among conflicting objectives within the system. Evolutionary Algorithms (EAs) are population-based global optimization methods inspired by the principles of biological evolution to identify optimal solutions. A set of conflicting objectives are associated with water planning problems. For example, urban water systems, especially in big metropolitan areas, rely on large amounts of inter-basin transfers that withdraw water from distant water sources, impacting the environment and consuming significant financial resources due to pumping. Water conservation campaigns can reduce water usage and the frequency of restriction periods, leading to a decrease of inter-basin transfers and decreasing energy costs, but result in decreased revenues for utilities, which limits the aggressive implementation of water conservation programs across the U.S.

The development of the CAS simulation-optimization framework is focused on the impacts of urbanization on system's sustainability in the long term, where dry periods play an important role. The concept of sustainability, however, embodies, not only aspects of low flow periods, but also includes flood control and stormwater management. One objective of the research presented here is the development and exploration of an environmentally friendly metric designed to assess the impact of urbanization on stormwater. The Hydrologic Footprint Residence (HFR) (Giacomoni et al. 2012) quantifies the impacts of urbanization on downstream water bodies by characterizing the inundation dynamics of storm events. The HFR captures the temporal and spatial hydrologic changes of a flood event passing through a stream segment by calculating the inundated area and the duration of the flood. HFR better captures the impacts of urbanization than other metrics such as peak flow, which is a typical design criteria of many Best Management Practices (BMPs). HFR can be used to assess the performance of BMPs and Low Impact Developments (LIDs), which are infiltration-based structures designed to better approximate the hydrologic flow regime to pre-development conditions.

The dissertation is divided into six chapters following this introduction. Each chapter is presented in the format of the Journal of Hydrologic Engineering. The second chapter presents the CAS approach in simulating the sustainability of water resources and urbanization (Giacomoni et al. 2011). Simulation experiments were designed and conducted to illustrate the interconnections among land and water uses through feedback loops. The third chapter contains a study simulating adaptive water demand management strategies using the CAS approach under historic and climate change hydro-climatology. The fourth chapter identifies optimal adaptive water management strategies by using an EA to maximizing the water utility revenue and minimizing the frequency of restrictions, while minimizing the volume of inter-basin transfers. These three studies were applied to a hypothetical study case, based on the water supply system of the city of Arlington, Texas. This city presently faces one of the highest rates of urbanization and population growth in the U.S. and constantly suffers from risk of water shortage due to extended droughts.

The next two chapters are studies related to the application of the HFR. First, the concepts and motivation behind the HFR are developed and tested on a hypothetical watershed and on a watershed located at the Texas A&M University campus, in College Station, Texas. An additional study explored the HFR to assess the impact of urbanization in the Village Creek watershed near Arlington, Texas, which is a larger watershed than the ones previously studied. In both studies, pre-development, post-development, and management scenarios, such as the implementation of LIDs and BMPs, are tested. A sensitivity analysis is also performed for land cover type, number, and length of stream reaches. The dissertation is concluded with a summary and some final considerations about the contributions that the CAS modeling paradigm brings to the field of water resources management and planning and how it can help to improve urban water systems sustainability.

CHAPTER II

A COMPLEX ADAPTIVE SYSTEMS APPROACH TO SIMULATE THE SUSTAINABILITY OF WATER RESOURCES AND URBANIZATION

Urban water resources should be managed to meet conflicting demands for environmental health, economic prosperity, and social equity for present and future generations. While the sustainability of water resources can depend on dynamic interactions among natural, social, and infrastructure systems, typical water resources planning and management approaches are based on methodologies that ignore feedbacks and adaptations among these systems. This research develops and demonstrates a new Complex Adaptive Systems approach to model the dynamic interactions among population growth, land use change, the hydrologic cycle, residential water use, and inter-basin transfers. Agent-based and cellular automata models, representing consumers and policy-makers who make land and water use decisions, are coupled with hydrologic models. The framework is applied for an illustrative case study to simulate urbanization and the water supply system over a long-term planning horizon. Results indicate that interactions among the decentralized decisions of individual residents can significantly influence system-wide sustainability. Adaptive management policies are included to restrict the water use and land use of consumers as the availability of water decreases. These strategies are simulated and assessed based on their abilities to increase the sustainability of the water supply system under the stresses of population growth, land use change, and drought.

Introduction

The task of water resources management is to support long-term resource planning and ensure that adequate water supplies are available to meet existing and future water demands. Water resources management is especially critical in areas of rapid urbanization, where water supply and demand may become unbalanced. The mechanics of urbanization effect water resources via two pathways: land use change alters the hydrologic landscape, and population and economic growth can increase the volume of water demands beyond extrapolated levels. To reduce new stresses on the water system, public officials adaptively restrict water and land use, as they observe current or forecasted water shortages. Due to the dynamics of the urbanization process and the adaptive choices of consumers and utilities, a socio-technical system may emerge, in which the system performance is governed by feedbacks and interactions among the social, natural and infrastructure components (Liu et al. 2007). For these systems, water sustainability cannot be approximated based on the simple aggregation of the performance of separate elements.

Numerical simulation and modeling approaches have a long history and wide range of application for studying and analyzing water resources systems, and these tools can be applied to study urban water resources sustainability. Simonovic (2000) identified two paradigms, the complexity paradigm and the uncertainty paradigm, that are expected to change the course of simulation approaches for the future modeling of water management. The complexity paradigm, in particular, states that water problems in the future will be more complex due to the need to consider domains that have previously been considered external to a rational system approach. New considerations, for example, include environmental and social impacts, population growth and an increasing need for resources, the importance of water quality indicators, and longer planning horizons. The conventional set of water resources systems analysis approaches have been limited to approaches that simulate diverse water sectors in isolation and model consumer behaviors as exogenous inputs. More specifically, tools that are readily available for water resources management neglect the potential consequences of consumer decisions to update land and water use behaviors. Engineering models typically consider water and land use activities as exogenous inputs, ignoring feedbacks, interactions, and adaptations to physical and other socio-economic processes (Prodanovic and Simonovic 2010; van Oel et al. 2010). Though individual residents make diverse and dynamic decisions at a lot-level about land and water use, these decisions are usually represented as a lumped demand at neighborhood levels. The research presented here addresses the complexity of environmental and social interactions with water infrastructure systems through the development of a dynamic modeling framework for water resources systems analysis that is designed to provide insights about the influence of feedbacks and adaptations on the emergent sustainability of urban water supply. A system, such as the urban water supply system, that is characterized by dynamic feedback loops and a set of decentralized actors who influence emergent system properties can be posed as a Complex Adaptive System (CAS) (Axelrod 1997; Holland 1995; Miller and Page 2007). This research creates a new CAS framework to integrate decentralized adaptations among population growth, land use change, consumer behaviors, utility decision-making, hydrologic processes, and water infrastructure to assess urban water resources sustainability. The framework analyzes and explores the interactions across these social, infrastructure, and environmental components of urban water systems and across diverse scales by coupling systems dynamics, cellular automata, and agent-based models with hydrologic modeling. The CAS approach is applied for a case study in Arlington, Texas, to simulate urbanization and its effects on the urban water system for a long-term planning horizon and to shed insights about the mechanisms that drive system-wide sustainability.

Dynamic Feedback in an Urban Water Cycle

Feedback loops emerge in an urbanizing watershed as the availability of water resources affect consumer decisions about water use, and, subsequently, consumer decisions affect water availability. Let *water availability* be defined here as the amount of water that is readily available for human consumption, environmental requirements, and all other uses after all inflows and outflows have been accounted at any time step in a planning horizon. For example, the storage in a surface water reservoir can be called water availability and is calculated as the initial storage minus human demands and environmental flows, plus the inflow from watershed runoff and direct precipitation. This research poses that there is a complex dynamic nature in calculating water availability, which arises because water availability can directly and indirectly influence consumer decisions to use water. For example, as communities experience water shortages and water scarcity, restrictions on outdoor water use and conservation campaigns may be implemented by the water utility. In response, residents may update water and land consumption behaviors by using water-efficient technologies, stormwater-reduction technologies (e.g., low impact development practices), and water conservation practices. The adoption of outdoor water use restrictions and water conservation measures reduce the overall demand of the community for both short- and long-term horizons, and decreases the water that is withdrawn from the reservoir. As a result, water availability may improve immediately or over a long-term planning horizon.

In addition to changing water use in response to water availability, consumers also make decisions about land use which influences their total water use and stormwater runoff generation, and these decisions can feed back into a water supply system to influence water availability. Land use changes in the development of residential, commercial, and industrial areas shape hydrologic characteristics, altering the runoff characteristic of newly developed parcels and impacting the water supply yield of surface water systems (US EPA 1993; US EPA 2004a). The population density that accompanies different development patterns, along with the indoor and outdoor water activities of consumers, drives the need for new water supply infrastructure. Moratoriums on development may be imposed by utilities to curb the addition of new demands and can also impact the evolution of land cover change. The implementation of policy and the consumers who comply will result in a reduction in water withdrawals and may allow a water supply system to recover from depleted conditions. Subsequently, consumers and decision-makers can re-evaluate and update land and water use decisions and restrictions.

The conceptual framework presented here includes three feedback loops in the urban water cycle, represented through causal loop diagrams (Figure 1). The causal loop diagram is a technique to represent cause-and-effect relationship within a closed chain process (Ford 1999). Positive or negative symbols are associated with each arrow to depict the polarity of the relationship between two variables. For a relationship where a positive change in one parameter creates a positive change in the receiving parameter, the polarity is positive; on the other hand, if a positive change in one parameter creates a negative change in the receiving variable, the polarity is negative. The polarity of the loop is the product of all polarities within the loop. Negative or balancing feedbacks, symbolized by a "-" symbol in the center of the loop, produce a system that can stabilize or find an equilibrium, while positive or reinforcing feedbacks ("+") result in system behavior that diverges.

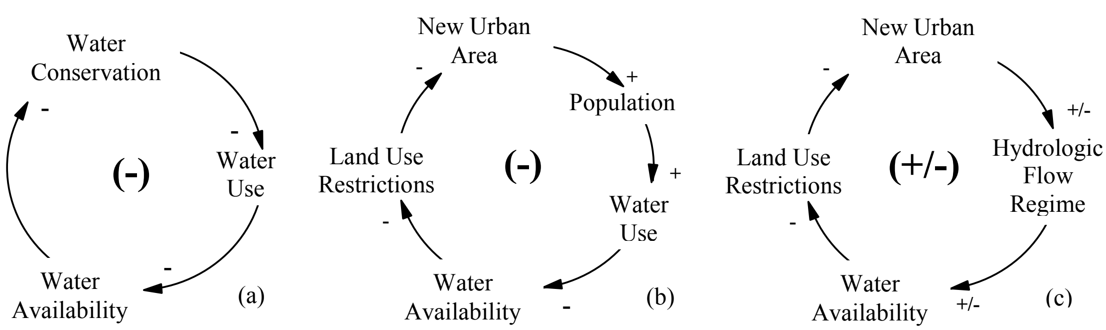


Figure 1. Causal loops diagrams for an urban water resources system.

In Figure 1 (a), the first loop represents the interactions among water availability, water demand and water conservation practices. As water withdrawals increase, water availability decreases, representing a negative causal interaction. In response to reduced water availability, consumers adopt water conservation practices and water-efficient technologies, and reductions in demand increase water availability. This is a negative or balancing feedback loop, which produces a stabilizing effect on the behavior of the system. Another feedback loop demonstrates the dynamics among land use policy, urbanization, population growth, water demand, and water availability (Figure 1(b)). The growth of urban areas causes increases in the total water demand as new demands are introduced. As a result, water availability decreases. Policy-makers may implement land use restrictions to slow development and restore water availability, creating a balancing feedback loop.

The third and final feedback loop describes the relationship between physical changes to the land cover and water availability (Figure 1(c)). The growth of urban areas creates new impervious areas, which increase the surface runoff produced during rainfall events, which can improve total water availability (effects on water quality are neglected here). At the same time, however, the volume of water that infiltrates and recharges groundwater reservoirs decreases, and this mechanism can lower the contribution of base flow to the streamflow and, consequently, the natural yield of the watershed. Land use change restrictions, as described above, limit the amount of new impervious areas and the resulting effect to the hydrologic flow regime. The effect on the hydrologic flow regime may be positive or negative, as the magnitude of the loss of base flow compared to the increase in surface runoff will depend on climatic parameters and watershed characteristics. Therefore, the last loop may be either a balancing or a reinforcing loop, and additional observations and simulation should be explored for a set of specific watershed characteristics to determine the polarity of this loop.

Complex Adaptive Systems Modeling Framework

A CAS approach is developed to simulate the dynamic feedbacks in an urban water system. CAS approaches describe and predict systems that exhibit complex behavior at the macroscopic level, emerging from the collective actions of many interacting components, and a CAS can be defined as a complex network of agents that are constantly adapting to their environment (Mitchell 2009). Agents are connected by a set of rules that govern how they react and adapt to other agents and to the environment. These rules are typically simple, but the collection of interactions causes a complex and unpredictable state of the system, which feeds back into the system to influence agent behavior (Holland 1995). In simulating a CAS, the states of each agent and of the system are updated at each discrete time step. Agent-based modeling and cellular automata are two methods for simulating a CAS. Agent-based modeling represents individual actors in a system as a set of potentially mobile, autonomous agents (Miller and Page 1997). A cellular automata system represents a landscape as a grid, where the state of each cell is updated at each time step using a transition rule that is based on the state of its neighbors (Wolfram 1983).

CAS-based approaches have been applied to model the dynamic interactions among components of the urban water system through a set of diverse studies. An agent-based modeling approach was used to explore the relationships among changes in land use, water use, and groundwater depletion and to test alternative restrictions that limit the density of development (Zellner 2007). Gallan et al. (2009) developed an agent-based modeling approach to integrate models of urban dynamics, water consumption, and technological diffusion to study the influence of social-economic mechanisms, including immigration, on water consumption. Rixon et al. (2007) implemented agent-based modeling to explore the effects of social networks and tariff structures on water use. To explore the supply side of water systems, Tillman et al. (2005) developed an agent-based model that represents a design engineer as an agent, who applies a set of rules to determine if the system should be expanded based on water availability and consumption trends. Athanasiadis et al. (2005) developed a modeling framework that incorporates both supply and demand side of a water distribution system, where consumer agents and water supply agents interact under a set of water pricing scenarios.

A new framework is developed here for urban water resources systems (Figure 2). This work builds on the research described above by representing a comprehensive urban water cycle, including a set of adaptive consumers who make both land and water use at the lot-level; an adaptive decision-maker who updates both land and water use policies based on the current water availability; and engineering models to mechanistically represent the rainfall-runoff and water supply processes. Cellular automata and agent-based modeling are used to represent land use change and lot-level water demands. A cellular automata model simulates the change of natural land use to urban areas through neighborhood-level interactions. The land use change model generates land cover information to serve as input to the hydrologic model, which computes a streamflow hydrograph that serves as input to the reservoir model. The land use change model also computes how much land is available for future urbanization, which creates input for a system dynamics model of population growth. The population growth creates new agents, and each agent applies a set of rules for indoor and outdoor water demand. Individual demands are aggregated as the total demand at each time step to simulate withdrawals and calculate the fluctuation of storage in the reservoir. Finally, an agent-based model represents a policy-maker, who defines urban growth and water conservation policies based on the volume of water in the reservoir. These policies serve as inputs to the consumer agent-based models and the cellular automata land use change model.

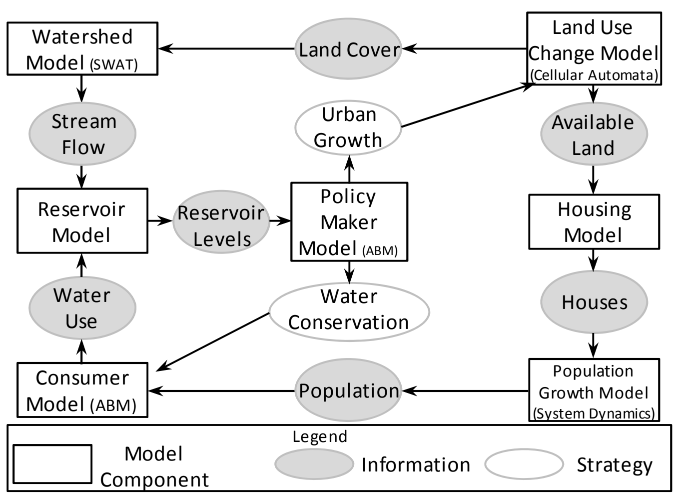


Figure 2. Schematic representation of the CAS modeling framework, which is composed of seven components: population growth, housing, land use change, watershed model, reservoir, residential water demand, and policy maker model.

The CAS framework was built using AnyLogic, which is an objected-oriented modeling environment designed for the formulation of dynamic models (XJ Technologies 2010). Each agent or mechanistic model component is implemented as an active object that is connected to other objects to send and receive information, which is represented as a packet of data or a message. An agent or model component consists of parameters that describe system properties and functions to specify behaviors. An agent can receive information about events, such as the passing of one time step or the receipt of a message from another agent, and call the appropriate function to perform actions and computations, automatically updating parameters and variables.

The CAS framework is designed to simulate processes that evolve in different time scales, and the separate elements have been properly synchronized. Land use change is simulated in an annual time step. At the beginning of each year, land cover information is passed to the hydrologic model, which calculates hydrologic processes at a daily time step. Daily streamflow values are aggregated to represent monthly inflow values that are used as input for the reservoir water balance. All other model components, including consumer water use decisions, volumes of water for interbasin transfers, and restrictions on water use, are simulated in a monthly time step. Modeling components are described in detail below.

Cellular Automata Land Use Change Model

Urban land use change is a complex and dynamic process between natural and human systems and can be simulated using a cellular automata model (Koomen and Stillwell 2007). The model computes the likelihood of an undeveloped cell within a grid to change its state to urban land use, based on the number of developed neighbors, distance to main roads, distance to minor roads, and distance to central areas. The likelihood, L, is the weighted sum of these factors:

$$L_{(x,y)}^{t+1} = \alpha \times N_{(x,y)}^{t} + \beta \times \left(1 - DMR_{(x,y)}\right) + \gamma \times \left(1 - DmR_{(x,y)}\right) + \mu \times \left(1 - DCa\right) + \varepsilon \times Rd_{(x,y)}^{t} \quad (1)$$

$$\alpha + \beta + \gamma + \mu + \varepsilon = 1 \quad (2)$$

where: α, β, γ, μ, and ε are weights; (x, y) indicates the coordinates of the centroid of the cell to serve as a unique identifier; and t is the time step. $N_{(x,y)}^{t}$ is the normalized function based on the number of developed neighbors; $DMR_{(x,y)}$ is the normalized distance to main roads; $DmR_{(x,y)}$ is the normalized distance to minor roads; $DCa_{(x,y)}$ is the normalized distance to central areas; and $Rd_{(x,y)}^{t}$ is an random number between 0.0 and 1.0. Values for coefficients α, β, γ, μ, and ε can be obtained by manual or automatic calibration to match model output with land cover data, as it is available over a sufficient time period. The prediction accuracy of the land use change model can be represented using the Kappa metric, which measures the spatial agreement between observed and predicted urban areas (van Vliet et al. 2011).

For each cell at each time step, the likelihood that is calculated using Eqn. 1 is compared to a development threshold function: if the cell likelihood is greater or equal than the value of the development threshold function, the cell will change land use to urban area; otherwise it will remain in the same state and be evaluated in the next time step. The development threshold function is:

$$\theta\left(\hat{t}\right) = -\left(a - b\right)\hat{t} + a \quad (3)$$

where θ is the development threshold value, which varies between 0 and 1; $\hat{t}$ is the normalized time period; *a* and *b* are coefficients. The development threshold function is a monotonically linear decreasing function, and it is used to mimic typical sprawl patterns, where development begins at a slow rate, quickly accelerates, and moves toward stability at late stages in the development, due to the scarcity of unoccupied land.

Population Growth System Dynamics Model

System dynamics (Forrester 1961) is a modeling technique that represents delays and feedback loops in a system using stocks and flows. System dynamics can be used to represent the underlying mechanisms of population dynamics that extrapolation equations may neglect (Alfeld and Graham 1976) and facilitates the representation of the interaction between land use change and population growth. The population growth is modeled as follows:

$$\frac{dP}{dt} = B + I - D - E \tag{4}$$

$$B = F \times P \tag{5}$$

$$D = \frac{1}{T} \times P \tag{6}$$

$$E = e \times P \tag{7}$$

$$I = i \times \lambda \times P \tag{8}$$

$$H_{new} = UA_{new} \times f_{density}(UA_{total}) \tag{9}$$

$$\lambda = f_{\lambda}\left(\frac{HH}{H}\right) \tag{10}$$

where P is the population, and dP/dt is the rate of growth of the population. The population growth is based on B, the rate of births; D, the rate of deaths; I, the rate of immigration; and E, the rate of emigration (Eqn. 4). B, D, and E grow with the population, based on a fertility rate, F; the average lifespan, T; and a normalized emigration rate, e, respectively (Eqns. 5-7). The rate of immigration, I, is based on a normalized immigration rate, i; and the attractiveness of housing multiplier, λ (Eqn. 8). The attractiveness of housing multiplier is calculated using information from the land use change cellular automata model. At each time step, the land use change model calculates the number of newly developed urban area, UA_{new}. As a city grows, the development tends to be increasingly dense, and a density function $f_{density}(UA_{total})$ calculates the number of new houses, H_{new}, that are constructed within each cell (Eqn. 9). This data is used to update the total number of houses, H, and λ is calculated as a function, f_{λ}, of the ratio of the number of households, HH, to H (Eqn. 10). HH is calculated as the population divided by the average household size.

Agent-Based Residential Water Demand Model

An agent-based model of residential consumers simulates indoor and outdoor water demands at a household level (Kanta and Zechman 2011). Each agent is assigned a series of stochastic monthly demands and lot size, which are generated using water utility data. Water use categories are constructed to allocate water use among indoor and outdoor uses for each agent, based on its lot size. Category 1 agents use water for indoor activities alone. Category 2 and Category 3 consumer agents use water for outdoor demands in summer months (June to November). During summer, 50% of the predicted demand is allocated for indoor uses, and the outdoor demand is computed using a garden end-use model, which calculates the demand based on the size of the lot and climatic inputs, and limits outdoor demands to no more than 50% of the predicted demand (Jacobs and Haarhoff 2004). Category 3 consumers use water for outdoor activities throughout the year. During non-summer months, 66% of the demand is allocated as indoor use, and the outdoor demand is computed using the garden end-use model and constrained to less than 34% of the total demand. The garden end-use model is:

$$AMDD_{o,m} = \min \begin{cases} \text{\% allowed demand} \\ \left(f_m \times s\right) \dfrac{\left(k_m \times p_m\right) - r_m}{d_m} \end{cases} \tag{11}$$

where $AMDD_{o,m}$ is the average monthly daily water demand (liters/day); f_m is the garden irrigation factor; s is the irrigable lawn area; k_m is the crop factor; p_m *is the* pan evaporation; d_m is the number of days during month m; and r_m is the effective rainfall during month m. The effective rainfall (r_m) represents the portion of actual rainfall, R_m (mm/month) that is stored in the soil.

Hydrologic Model

The model Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) is coupled within the CAS framework to represent the main hydrologic components of a watershed. SWAT is a continuous river basin scale hydrologic model developed to simulate watershed land management practices and a set of water quantity and quality variables for receiving water bodies (Neitsch et al. 2005). SWAT has been used for watershed management to assess the effect of land use change and urbanization on water quantity and quality (Franczyk and Chang 2009; Miller et al. 2002; Tong et al. 2009). The model requires input information regarding land use, soil types, topography, weather, and land management practices. A watershed is simulated as a set of discrete subwatersheds, and each subwatershed is divided in hydrologic response units (HRUs), where vertical flows such as evapotranspiration, precipitation, infiltration, and runoff, are calculated. The cellular automata model calculates new land cover information on an annual time step and updates input data for SWAT. Within each subwatershed, the fraction of an HRU that is covered by urban land use increases when corresponding cells become urbanized, and the fraction of the HRU associated with non-urban land cover types, including agricultural and forest, is decreased.

Reservoir Model

A reservoir system is implemented within the framework to describe storage and level fluctuations in monthly time steps. Inflows to the reservoir are streamflow, direct rainfall, and inter-basin transfers, and outflows include lake evaporation, release, withdrawal for consumer and industrial demands, and spills. The surface area is calculated using a stage-storage curve and regulates the amount of evaporation and rain that falls directly into the reservoir. At the beginning of each month, the reservoir model receives streamflow values from the hydrologic model; the volume of water pumped into the reservoir from the Policy-Maker model; and the volume of withdrawals from the Consumer Model. The final storage at the end of the month is computed and used as input to the Policy Maker for selecting water policy decisions in the subsequent month.

The Policy Maker uses minimum monthly storage level of the previous year to set the land use change and development policies for the following year.

Agent-based Policy Maker Model

The agent-based Policy Maker model is a single agent model that receives information about the surface water elevation from the reservoir modeling component on a monthly time step and, based on reservoir storage, defines the level of water restrictions and the allowable rate of land use conversion. The policy agent restricts water use for the consumer agent-based models by imposing a reduction in the number of times per week that each consumer agent can use water for outdoor purposes. The policy is implemented in three stages, Drought Stages 1, 2, and 3, which correspond to decreasing reservoir storages. Irrigation factors used in the outdoor irrigation equation (Eq. 11) are reduced as the stages increase, from 2.0, to 1.0, 0.5, 0.0, to represent irrigation frequencies of five, two, one, and zero times per week, respectively. The water restriction rule represents a typical municipal strategy for reducing residential water use during drought periods.

The policy agent also enforces an adaptive land use change strategy, which allocates an allowable rate of land use change based on the minimum volume of water stored in the reservoir in any month of the previous year. An additional parameter, τ, is defined to increase the threshold likelihood for development, which increases with Drought Stages (as defined for water use restrictions). At each time step, the model calculates L, the likelihood of an undeveloped cell to become urbanized (Eqn. 1), and θ, the value of the development threshold (Eqn. 3). Based on the Stage, the value of τ is selected and added to the development threshold (shown in Eqn. 12). If the likelihood of an undeveloped cell is greater than or equal to the sum of θ and τ, the cell changes its state to urban:

$$if \;\; L^{t}_{(x,y)} \geq \theta + \tau \rightarrow LU_{(x,y)} = Urban \tag{12}$$

This land use change restriction rules represents economic moratoriums and development policies for reducing urban growth that can be implemented during periods of drought.

Illustrative Case Study

The CAS framework is applied to simulate a part of the water supply system of the City of Arlington, TX, located south of the Dallas/Fort Worth Metropolitan region (Figure 3). The City of Arlington covers 255 square kilometers and has a population of approximately 390,000 inhabitants, and the population of Arlington is projected to increase to 472,000 inhabitants by the year 2060 (Freese and Nichols et al. 2010; TWDB 2007).

Approximately 55% of the City's residential demand is provided by water stored in Lake Arlington (Freese and Nichols 1999). The Village Creek Watershed empties into Lake Arlington, draining 370 sq. km of primarily agricultural land. In 2009, the city corporation limits included 6.7% of the watershed area, and as the population grows, it is expected that the city boundaries would expand to encompass more area within the watershed and convert natural land cover to urban uses.

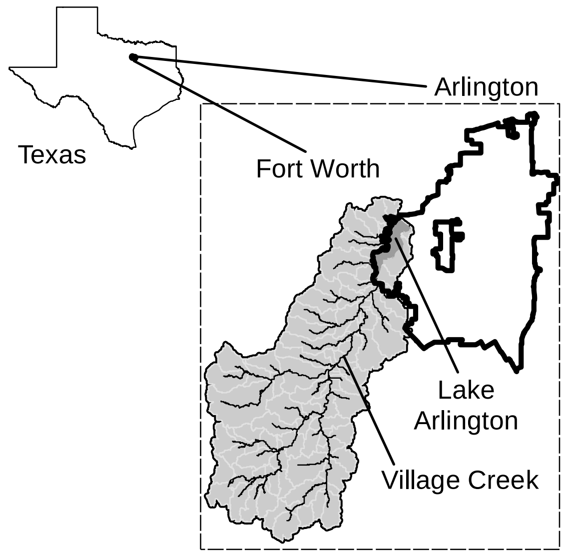


Figure 3. Location of the city of Arlington (dark line), land use modeling area (dash rectangular) and Village Creek Watershed (gray).

Arlington Land Use Change

The cellular automata modeling approach is used to simulate the land area that encompasses Arlington corporation limits and the Village Creek Watershed (Figure 3). The land area of 1,574 square kilometers is divided into 39,338 cells of 200 meters by 200 meters, and each cell is classified as urban or non-urban. The model is initialized using land cover for 1973 and calculates transitions of cells from non-urban to urban in an annual time step. The cellular automata model was calibrated and validated using satellite images that are available through LandSat for the years 1973, 1979, 1986, 1992, 2001, and 2009. These images were converted to land use data that describes each cell as urban or non-urban using a supervised classification method (Camara et al. 1996). The cellular automata model was calibrated using the automatic optimization procedure

Optquest (Glover et al. 2003), which is an evolutionary algorithm that is available within the simulation framework, AnyLogic. The Kappa metric (van Vliet et al. 2011) was maximized for a calibration period (years 1973, 1979, and 1986) to identify values for the cellular automata parameters. The years 1992, 2001, and 2009 were used to validate the model. The performance of the calibrated cellular automata model for calibration and validation data is shown in Figure 4 (a), which compares the simulated urban land use with historical data.

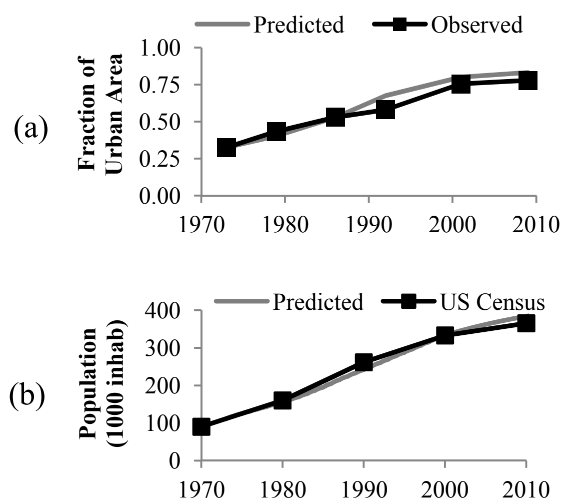


Figure 4. (a) Observed and simulated fraction of the simulated area that is urban land use, and (b) observed and simulated population within the City of Arlington.

Arlington Population Growth

Population growth was simulated for the City of Arlington from 1973 to 2009 and compared to US Census population data for this period (Figure 4(b)). Eqns. 4-10 were calibrated to simulate historic data by adjusting values for model parameters, including normalized immigration rate, i; normalized emigration rate, e; and values for parameters within the empirical functions, f_λ and $f_{density}$, that relate land availability to immigration rates and housing densities, respectively. The household size is 2.4 individuals, based on US Census.

Arlington Consumer Agents

The city of Arlington Consumer agent-based model was initialized with 48,500 agents to represent each household that draws water from Lake Arlington. Consumer agents are grouped into categories based on billing data available through the City of Arlington (Kanta and Zechman 2011). Each agent is assigned a lot-size based on census data (U.S. Department of Housing and Urban Development 2002), and an agent is assigned one of three water use Categories based on lot sizes of less than 0.05 hectares; 0.05 – 0.1 hectares; and greater than 0.1 hectares. Distribution of consumers among water use Categories 1, 2, and 3 is 12%, 41% and 47%, respectively.

Arlington Policy Maker Agent

The policy maker agent was implemented using the reservoir storages of 75-100%, 60-75%, 45-60%, and 0-45%, to represent Drought Stages 0, 1, 2, and 3, respectively. Corresponding to the Drought Stages, the number of days during which consumers may water their lawns decreases, at five, two, one, and zero. The value of τ, as used in Eqn. 12, increases to represent tightening restrictions on land use development, at values of 0.0, 0.02, 0.04, and 0.05 corresponding to Stages 0-3. Stages

0-3 are defined by the City of Arlington's Drought Contingency and Emergency Water Management Plan (City of Arlington 2008).

Village Creek Watershed and Reservoir Simulation

A model of the Village Creek Watershed is implemented using SWAT. The watershed is subdivided in 95 subwatershed and 469 hydrologic response units (HRUs) to represent unique combinations of five land cover types (urban residential, commercial/transportation, agriculture, forest, and water bodies) and hydrologic soil types B, C, and D. Lake Arlington has a total reservoir capacity of 49.6 million cubic meters at conservation pool elevation (167.64 meters above mean sea level), which inundates an area of 7.79 square kilometers (TWDB 2008). Water supply in Lake Arlington is supplemented with interbasin transfers, which are implemented to ensure a target storage at the onset of summer and to allow fluctuations during high demand periods. The modeling framework uses a constant pumping schedule instead, which is the ten-year average pumping volume calculated for each month (1999 – 2008). The constant pumping scheme that is used in the simulation framework minimizes the influence of external transfers of water into Lake Arlington and allows the analysis of the modeling framework to isolate the dynamics that arise from the adaptive behaviors of actors.

Simulation Scenarios

Two simulation models are evaluated, a CAS Model and a CAS Policy Model. The CAS Model simulates the dynamic interactions among land use, residential water consumption, hydrologic cycle, and reservoir operation, and the policy agent does not take any actions to enforce adaptive management strategies. The CAS Policy Model includes, in addition to the processes simulated in the CAS Model, an active policy agent, which enforces adaptive water and land use policies. To assess the dynamic interactions among all the components of the system, three input settings were selected to represent a range of rainfall and climatic signatures. The Mid-1, Mid-2, and Mid-3 Scenarios represent three years of rainfall that are close to average annual depths (903, 892, and 834 mm, respectively) (Figure 5). Each rainfall signature was repeated for a simulation period of 50 years. By using experiments that repeat the same rainfall pattern each year, the influence of the high variability of climatic inputs is alleviated, and the analysis focuses on the interactions among system components. The model is initialized with the 1973 land cover; the reservoir begins at the conservation pool level; and the population of approximately 111,000 individuals is represented as 48,500 agents, or households.

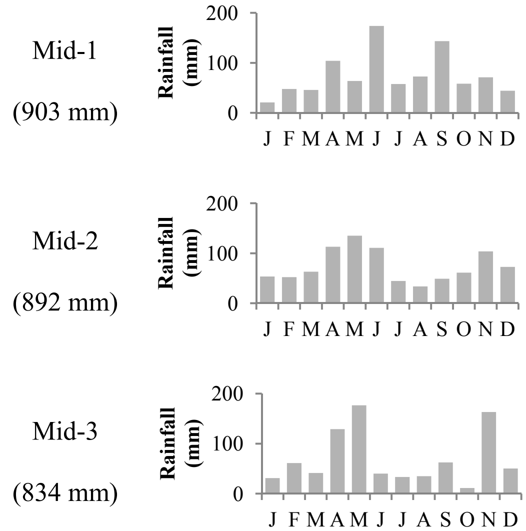


Figure 5. Monthly rainfall distribution of three climatic scenarios.

Results

System Dynamics for Mid-level Rainfall Signature (Mid-1)

In the Mid-1 CAS Scenario, the Mid-1 rainfall signature serves as input for execution of the CAS Model. Results are shown in Figure 6, which includes the time series data of the urban area growth inside the city and watershed boundaries, household demands, average annual inflows into the reservoir, and reservoir storage. The performance of the system, which can be measured as the reservoir storage, is driven by the growth of urban area (Figure 6 (a)). During the first part of the simulation, most of the urban growth occurs within the existing city boundaries, which is outside the watershed boundaries. Urban growth follows an *S*-shaped curve, where slower urbanization rates occur in the early periods of the simulation, increasing exponentially until the rate of development stabilizes at approximately year 30. Within the City of

Arlington, the urban area grows from 83 to 215 km^2. Urban growth inside the watershed increases exponentially after almost no growth in the first 20 years, increasing from 79 to 199 km^2. The population of the city of Arlington increases from 48,500 to 174,583 agents or households (approximately 111,000 to 419,000 residents). Water demands rise with the population and the maximum monthly demand increases from 2.50M m^3 in the first simulated year to 9.15M m^3 in the last year (Figure 6 (b)). The growth of urban area inside the watershed decreases the total inflows to the reservoir, which show a small reduction over the period of the simulation (Figure 6 (c)). This is because the loss of base flow due to new impervious areas is greater in magnitude than the increases in surface runoff, and the overall watershed yield decreases with time.

Storage in the reservoir results from the interactions among all these processes (Figure 6 (d)). Reservoir dynamics show little variation among the first 25 years, and the reservoir storage reaches maximum capacity during non-summer months. At approximately year 25, urban sprawl crosses the boundaries of the city and spreads into the watershed in an upstream direction. Population also continues to grow within the city, and as the reservoir cannot sustain the increasing volume of demands, storage in the reservoir starts to decease. Each year, the reservoir drops in elevation during the summer months, and after approximately 25 years, the annual outflow exceeds than the annual inflow (Figure 6 (c)). The reservoir levels continue to drop, and by year 35, the storage is depleted during summer months, and the system cannot fully recover.

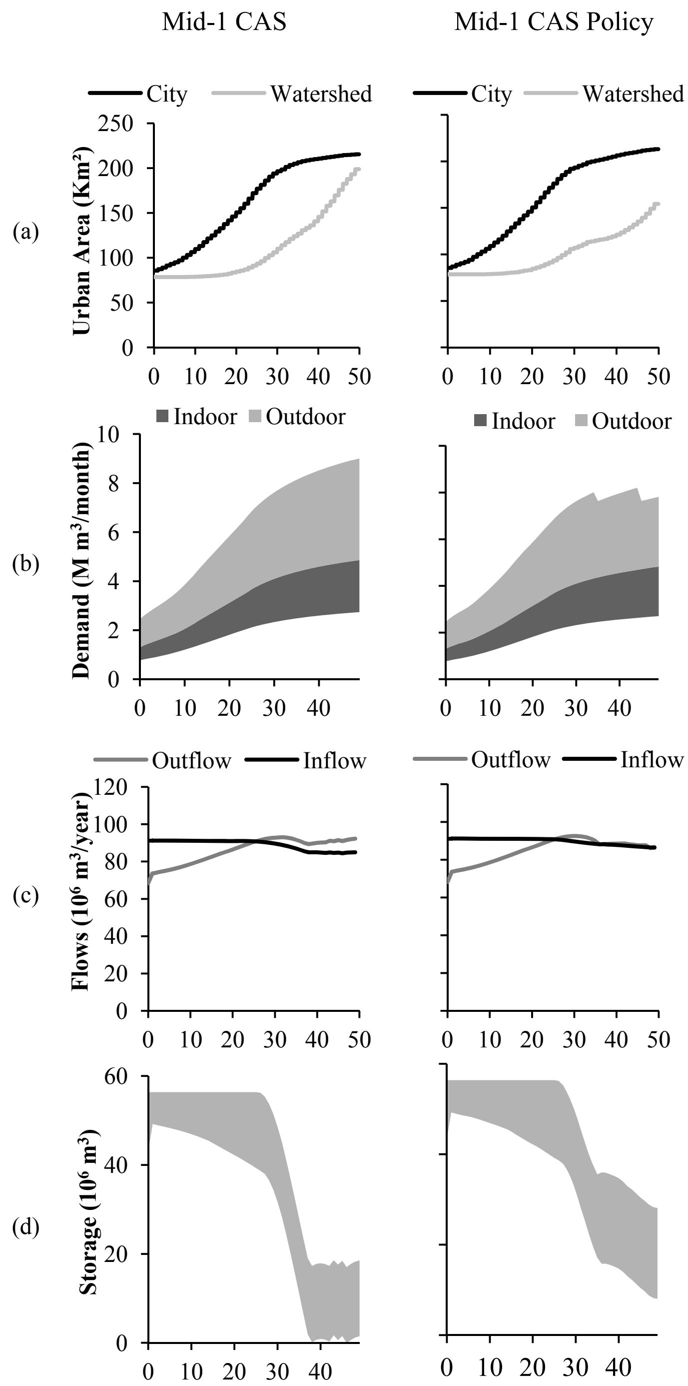


Figure 6. Urban area for the City of Arlington and Village Creek Watershed, indoor and outdoor demand, yearly inflows (streamflow, rainfall, and pumping) and outflows (residential and industrial demand, evaporation, and spills), and reservoir storage for the Mid-1 CAS scenario and the Mid-1 CAS Policy Scenario.

The CAS Policy Model (called the Mid-1 CAS Policy Scenario) was simulated using Mid-1 rainfall pattern. The growth of the urban area within the city does not differ from the CAS Model until year 30, when growth is kept at a slightly lower rate through actions of the policy agent (Figure 6 (a)). The final urban areas for the city and the watershed are reduced by 0.47% and 21.6%, respectively, when compared to the Mid-1 CAS Scenario. There is only a small difference in indoor demands between the CAS and CAS Policy Model, as the population that withdraws water from Lake Arlington is within the city limits and is similar between the two scenarios (Figure 6 (b)). The outdoor demands are affected in later time steps as the Policy agent restricts water for outdoor water activities in response to low storage in the reservoir. As shown in Figure 7, Stage 1 for the water conservation and land use restriction policies are not activated until the reservoir surface drops below 75% of the conservation pool, or at approximately year 30. As the reservoir level continues to drop, Stages 2 and 3 are implemented. When the adaptive policies are included in the simulation, the inflow and outflows of the system are balanced (Figure 6(c)), and storage is maintained in the reservoir during the 50-year simulation period (Figure 6 (d)).

Sensitivity of Feedbacks to Rainfall Signatures

The system performance was simulated for additional rainfall signatures using the CAS Policy Model with the Mid-2 and Mid-3 patterns as input (**Figure 8**). The depths of annual rainfall for Mid-2 and Mid-3 are 98% and 92% of the Mid-1 depth, respectively. These two signatures have only a small decrease in the volume of rainfall, and results are driven not only by the amount, but also by the timing of the rainfall.

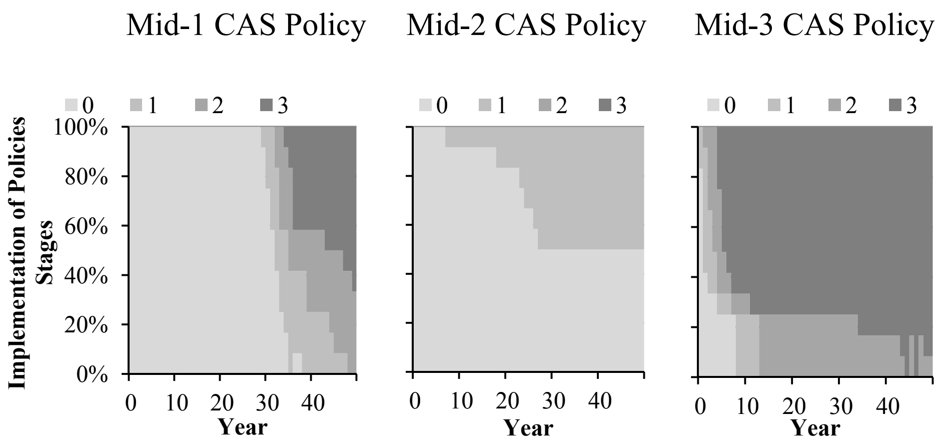


Figure 7. Implementation of water conservation strategy stages for the Mid-1, Mid-2, and Mid-3 CAS Policy Scenarios. The y-axis represents the percent of time each stage the system is in each year.

For the Mid-2 CAS Policy Scenario, urbanization of land use inside Arlington boundaries and population is restricted at time step 8, when the reservoir level drops below 75% of the conservation pool (Figure 7). At that time, urban development inside the Village Creek watershed is slowed through these adaptive policies. The decrease in development curbs the indoor and outdoor consumption volumes, and the storage in the reservoir is not depleted during the summer months. The system was simulated for an extended planning horizon to reveal that the reservoir stays in equilibrium for approximately 28 years past the original 50-yr projection before the reservoir becomes depleted. Though the Mid-1 CAS Policy Scenario uses a rainfall pattern with a greater depth than the Mid-2 CAS Policy Scenario, the reservoir storage is depleted earlier in the Mid-1 Scenario. This is because the Mid-1 Scenario generates low rainfall depths in the summer months, when demands are highest, and high rainfall depths in the non-summer months. As a result, water is spilled and not available for use later in the year. For the Mid-2 Scenario, the rainfall occurs more uniformly throughout the year, and water is available in the reservoir during the summer.

The Mid-3 CAS Policy Scenario produces the lowest rainfall depth of the three scenarios, and the total rainfall fails to sustain storage in the reservoir. Though policies are enacted quickly (Figure 7), these activities are not enough to balance supply and demand, and the reservoir becomes depleted after 15 years (**Figure 8** (d)). Outdoor demands are restricted under Drought Stages 1, 2 and 3 throughout the simulated period. During the last ten years, there are two years during which no water is allowed for outdoor purposes at all. Though the amount of rainfall is not significantly less than the rainfall for Mid-1, the lack of rainfall in the summer months and the stress of new demands from population growth produce drought conditions for the Mid-3 Scenario.

Discussion

The modeling framework that is developed represents the interconnections among urbanization, land and water use restrictions, and urban water resources through three feedback loops (Figure 1). One feedback loop connects water availability, land use strategies, and new urban area with hydrologic processes including groundwater recharge, base flow, and surface runoff generation. Many hydrologic and watershed studies have focused on peak discharges, increase of storm runoff volume, decrease of time for runoff reach stream, increase frequency and severity of flooding, loss of baseflow, and greater runoff and stream velocity during storms for rainfall events (Choi and Deal 2008; Marshall and Randhir 2008); however, because urbanization also decreases infiltration rates, it is not clear if the loss of base flow or increase in surface runoff would dominate the amount of water leaving the watershed and entering the reservoir over a long-term planning horizon. Results presented here indicate that the influence of changing land use to impervious cover may depend on the climate; the Mid-1 Scenario resulted in a decrease in inflows, while all other rainfall patterns experienced a negligible change in inflows. Additional research is needed to investigate the relative contribution of inflows from base flow and surface runoff under increasing urbanization and determine the most effective land use policies for controlling any detriment to the natural flow regime.

A second feedback loop that is represented in the new framework connects water availability, land use change strategies, and urbanization. The dynamics between land availability and population growth have been represented here through a simplified approach that assumes that land use regulation influences the housing market and slows immigration. For application to the Arlington case study, the land use policy limits new impervious areas in the watershed, but does little to slow population growth and water demands, as the growth of the population that withdraws from Lake Arlington occurs early in the simulation within the city boundaries. For an area where development occurs within the watershed that contributes to the water source, restrictions on land use development can have more influence in restricting new water demands.

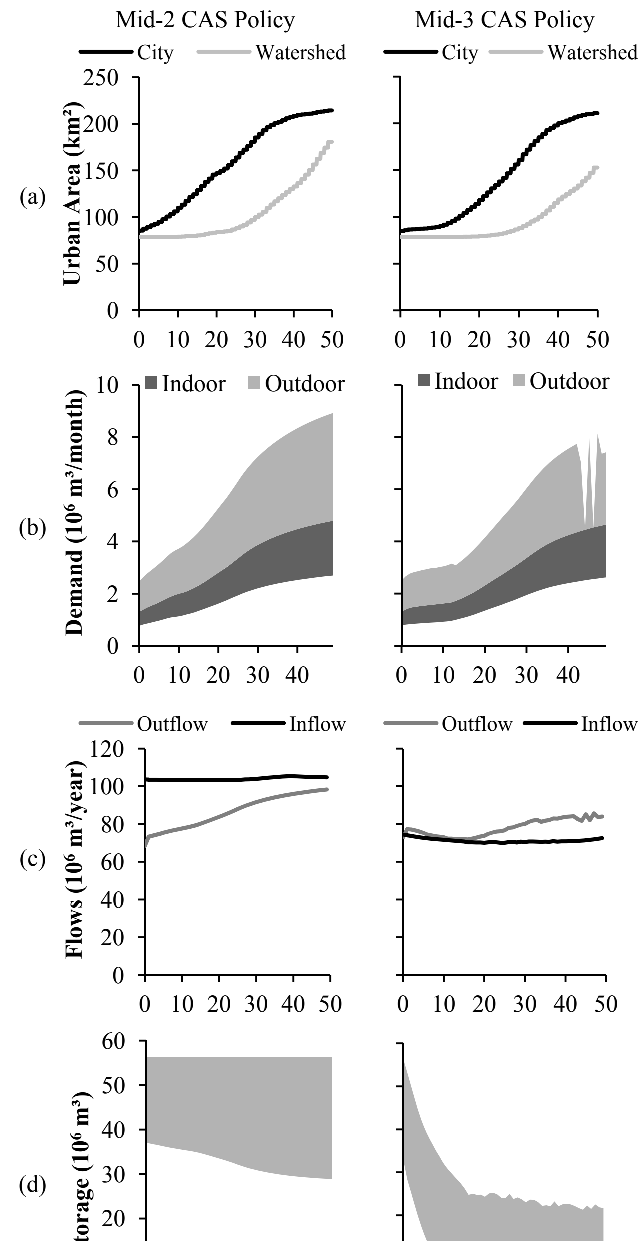


Figure 8. Urban area for City and the Watershed, indoor and outdoor water demand, inflows (streamflow, rainfall, and pumping) and outflows (residential and industrial demand, evaporation, and spills), and reservoir storage for the Mid-2 and Mid-3 CAS Policy scenarios.

A feedback loop also connects water availability, water conservation strategies, and water demand. Specifically, drought management strategies are simulated to restrict outdoor water uses, as many water utilities implement similar measures during water shortages. For the study explored here, outdoor use varies from 24 to 35% of the total demand, and drought management has a significant impact. While consumers are simulated here as complying with lawn watering restrictions, more realistic simulation should consider that some consumers will not comply and others may use excess water for lawn care at the threat of restrictions. The reality of consumer behaviors may require more active demand management to sustain water resources. The rules that govern agent's behavior are simple and static. New research about consumer behaviors and reactions can be incorporated in the framework through the development of new modeling that would simulate agents who learn and identify new rules for making water use decisions.

The framework presented here provides a method for quantifying the influences of dynamic feedbacks within the urban water system on the sustainability of the water resources system. For example, as shown in Figure 6, the annual total demands of consumers are reduced by 7.4% for an average rainfall signature when the feedback of policy decisions are included (Mid-1 Policy scenario), compared to simulations that neglect feedbacks (Mid-1 CAS scenario). Overall, the feedbacks create a balancing loop, so that depletion of the reservoir is postponed for approximately 25 years, compared to the Mid-1 CAS scenario.

Conclusions

The work presented here demonstrates a methodology and a modeling framework to simulate an urban water resources system as a CAS. The proposed CAS framework provides a new modeling technique for water resources systems analysis that can be used to develop and assess flexible management strategies and operation rules for complex water management problems. Social, infrastructure and environmental performance indicators are integrated and calculated through the CAS framework. For example, service reliability, infrastructure health, and hydrologic disturbance, can be used to assess sustainability and facilitate the decision making process.

A hypothetical case study based on the City of Arlington, Texas, was used to test the methodology. The modeled system includes several simplifying assumptions that do not reflect Arlington's water supply system as it is currently operated; rather, the experiments conducted in this paper were designed to illustrate the interconnections among the processes of land and water use that occur in many systems. Analysis of the results compares a dynamic simulation without feedbacks due to policy, and a CAS Policy scenario, where feedback loops update land and water use restrictions based on reservoir storage. The results demonstrate the influence of urbanization on the hydrologic cycle and pattern of demand consumption, and ultimately, on the sustainability of the water resources system. By including adaptive policies in the simulation, the influence of feedback is explored for its ability to restore balance to the water resources system. A set of rainfall patterns demonstrates the interactions of components and the system-level performance for average climatic conditions. Rainfall signatures representing extreme conditions can also be simulated and explored using the framework. For example, in an extended drought, adaptive policies are enacted immediately and the system stays in Drought Stage 3 indefinitely without any recovery. For simulation of a wet climate, the system operates without implementing any restrictions on water or land use.

Many of the processes represented in the framework are complex in nature. The lack of readily available spatial and temporal data, such as accurate land cover information, demographic characteristics of a population, housing units, household water demands, and other commercial, industrial and agricultural demands, is a limitation for implementing the modeling approach for data-scarce regions. Calibration and validation were performed for individual model components separately. Uncertainty in one process can propagate among other model components, and future work should investigate any amplification of uncertainty that could occur due to the feedback loops in the modeling framework.

The CAS Policy Model provides a new approach for evaluating sustainability for future demands. Existing paradigms for water resources planning project future water demands under different scenarios based on population growth predictions and evaluate supply alternatives to meet increasing demands. Water demand reduction targets are often incorporated in the planning process, but demand reduction depends on a variety of technological, social and economic aspects that may not be accurately represented as a lumped target value. Demands may shift as water resources become increasingly scarce, and models that are readily available do not consider the dynamics between scarcity and demands as they influence the total water availability. The CAS framework allows representation of the social aspects that influence diverse and decentralized demands and interconnects these to natural and infrastructure components through feedback loops. Due to the highly variable nature of water resources systems, ranging from prolonged scarcity to flooding, management that can adapt to different conditions may increase system efficiencies and sustainability. Future work can use formal approaches to identify optimal adaptive water and land use policies that maximize the sustainability of urban water systems.

CHAPTER III

SIMULATION OF ADAPTIVE DEMAND MANAGEMENT FOR URBAN WATER RESOURCES SUSTAINABILITY USING A COMPLEX ADAPTIVE SYSTEMS APPROACH

The management of urban water resources is challenged by population growth and climate change, which cause increasing water demands and future supply uncertainties. New water resources management methodologies are needed to help address increasing demands and future uncertainty. Adaptive water demand management can help systems to operate more efficiently increasing flexibility and adapting to increasing stresses, such as droughts. This study simulates water demand adaptive management in a big metropolitan city of United States that historically suffers from severe droughts. Historic and projected climate change hydro-climatic time series are used to assess the effectiveness of domestic water restrictions, demand reduction targets, rainwater harvesting rebate program, and a high density land use change policy. Each of the strategies are adaptively implemented, function of the amount of water storage available. The results show the combination of different policies better cope with the increasing stresses caused by urbanization, population growth and climate change.

Introduction

Climate change, land use change, and population growth, threaten the ability of water resources systems to sustainably balance water supply and demands. Because of climate change phenomena, uncertainties of future water availability are higher and the premise that historic hydrologic time series can provide guidelines for future water management may be an invalid assumption (Milly et al. 2008). Land use change, particularly in peri-urban areas, increases runoff rates during storms, increasing the extent and frequency of flooding and erosion, and decreases infiltration rates, which potentially decreases groundwater recharge. Rapid population growth and urbanization increase water demands to unsustainable levels, depleting existing water supply sources. New paradigms for water resources management paradigms should address the issues of increasing stresses and future uncertainty through flexibility that is designed to adapt to changing conditions.

The sustainability of urban water resources results from dynamics among human decision-making, environmental processes, and infrastructure performance. Urban water infrastructure systems, including reservoirs, pipelines, and water treatment plants, are designed for the provision of water for residential, commercial and industrial needs. Households and individual consumers make decentralized decisions about land and water use. Lot size and impervious cover affect the hydrologic regime through altering the timing and volume of stormwater runoff, and new development increases community demands for water supply and water delivery infrastructure. Utility managers design operating procedures for infrastructure, such as reservoir operation and inter-basin transfers, and during drought periods, utilities may impose water conservation measures using an adaptive approach. As the system loses water storage, utilities respond by encouraging consumers to reduce water demand through voluntary or mandatory water use restrictions, increased incentives for water efficient appliances, and educational campaigns.

Adaptive management was first proposed for improved and multidisciplinary management of natural resources by Holling (1978), and Walters (1986) has defined adaptive management as the process of predicting the impact of alternative policies by integrating interdisciplinary knowledge into dynamic modeling. Adaptive management can improve water systems efficiency by allowing adaptation to changing conditions. Most of the literature on adaptive management has been focused on theoretical frameworks and empirical analysis (Habron 2003; Pahl-Wostl 2008; Pearson et al. 2010; Prato 2003). Some studies have simulated adaptive management to model and manage the adaptation of water system operations to the uncertainties of climate change. Georgakakos et al. (2011) applied an adaptive management framework, that uses a longer-term simulation-optimization risk assessment than traditional practices, for a system of reservoirs under climate change scenarios. Westphal et al. (2003) developed a real-time decision support system to incorporate daily and weekly decision making allowing the system to adapt to as more information become available or as the system changes. In both studies, adaptive management outperformed traditional operations.

For this study, adaptive water demand management includes conservation or contingency rules that are implemented in different levels according to the amount of water available in the system in a specific time. Such mechanism creates a feedback between the demand and supply-side. If the system has enough water to supply all the demands, restrictions and conservation measures are alleviated. In periods of water scarcity, however, water demands are restricted, helping the system to recover faster. This managing paradigm may seem inefficient because it reacts to periods of crises rather than developing long-term management strategies. The representation of adaptive management implemented here, however, reflects the increased willingness of communities and decision makers to improve water management during periods when water problems are more visible to public, such as during droughts and water shortages.

The simulation of adaptive management for water resources sustainability requires computational frameworks capable of representing interactions, feedbacks and adaptations among social, natural and infrastructure components. Complex Adaptive Systems (CAS) (Holland 1995) are characterized by a set of decentralized agents and an environment that interact through dynamic feedback loops and are capable of better simulating adaptive management for urban water resources systems. Giacomoni and Zechman (2010) developed a CAS framework that couples system dynamics, cellular automata, and agent-based modeling to simulate population growth, land use change, household consumptions, hydrologic processes and water infrastructure for an urban water resources system. The CAS framework simulates components of the supply and demand sides, such as consumer water use, reservoir dynamics, and hydrologic cycle and is well suited for assessing the impacts of water conservation practices in the system because of the decentralized fashion of modeling water consumers and water managers.

This research extends the CAS framework to simulate adaptive water demand management strategies for an urban water resources system.

Adaptive management simulation is important because it provides a method to assess the performance of the management practices. The CAS framework can help to answer questions related to which practices are more effective in reducing water demand, how different adaptive demand management strategies interact, and what are their impacts in the short and long term. These types of question can give water managers better support for planning and decision- making. This new approach is applied to an illustrative study case of a big metropolitan area in United States that faces high rates of urbanization and historically has been suffering of periodic cycles of severe droughts.

Urban Water Demand Management

During 1990-2010, increasing environmental awareness and financial constraints, associated with economic and population growth, shifted urban water management from supply augmentation to demand conservation (Galan et al. 2009). Water conservation practices, such as water recycling and water conservation technologies, are implemented by water utilities and authorities to decrease the amount of water consumed by customers. Rebate programs are offered to households to install low-flow equipment (e.g., toilets, dishwashers, washing machines), replace high water demand lawn species to more drought resistant plants, and replace inefficient plumbing equipment. Decentralized supply enhancement can be incentivized to encourage households to rely on an alternative source of water, especially for outdoor water use. Comprehensive water management planning should also consider other urban water sector plans, such as demographic and land use zoning. New development occurs with the development of water infrastructure, and the integration between land use and water planning can generate efficiencies in water resource use for a long-term planning horizon and may prepare the system for low water availability periods.

Many water utilities and suppliers have developed drought plans that define demand management strategies to mitigate impacts of drought (TCEQ 2005). Drought plans typically include response stages, triggering criteria, system-wide or individual target demand reductions, and best management practices for reducing demands and meeting defined targets. Typically, priorities of uses are defined and restrictions to non-essential uses such as garden irrigation, swimming pools, and car washing are voluntarily complied or enforced by the public authority. A drought plan should clearly define the triggers that initiate and terminate each stage. Usually, drought triggers are based on hydrologic variables that are easy to define such as reservoir storage, streamflow, or groundwater levels (Fisher et al. 1995). Shepherd (1998) evaluated the effectiveness of drought contingency plans in the United States and concluded that drought plans have low effectiveness when elaborated and executed apart from larger scale and longer term water resources planning.

An alternative demand management practice is supply augmentation. Rainwater harvesting systems can provide a complementary source of water supply for non-drinking uses (Villarreal and Dixon 2005). A significant area of urban development is composed of roofs that can be adapted to collect rainwater with a relatively low cost for users or municipalities. Besides the benefits of supplemental water supply sources, rainwater collection systems also reduce stormwater runoff and potential urban pollution (US EPA 2008). Such an alternative is a common practice in rural areas, but only more in recent times it started to be more implemented in large metropolitan areas (Khastagir and Jayasuriya 2010). The use of rainwater harvesting is being encouraged by water agencies and utilities in many states within the United States and abroad.

Another water conservation and drought management practice that can alleviate the impact of droughts in urban water supplies systems is the control of new demands by land use regulations. Population growth and land use change have a direct impact on the amount of water usage in a community. Low density developments, often found in suburban areas of large U.S. cities, have a higher per capita water consumption than higher density developments because they have a larger amount of outdoor water usage (Western Resource Advocate 2003). Land use planning that prioritizes high-density development over low density development has the potential to decrease water consumption and improve urban water resources sustainability. High density development can also have other benefits, such as the reduction of contaminants in stormwater in a watershed scale (Jacob and Lopez 2009), reduction of green-house gas emissions and energy use (Norman et al. 2006), among other benefits.

The effectiveness of each of the water demand management strategies are a function of many social and technical aspects (Pahl-Wostl 2007). For example, the success of a rebate campaign for installing low-flow devices depends on economical aspects, such as the household level of income, as well as environmental awareness of the population that can be willing to invest more or less in environmental friendly devices. Realistic assessment of water demand management needs to take into account temporal and spatial dispersion of technologies. The socio-technical characteristic of urban water resources systems and adaptive management, require modeling frameworks with capabilities of simulating interactions among the many aspects of the environment, the society and infra-structure.

Complex Adaptive Systems Modeling Framework

Adaptive management in urban water systems creates feedback loops between social, natural and built components that are difficult to represent in typical input-output models. In a lower level scale, decisions of consumers about water and land use affect the state of the system. In the lot scale, households consume water that is a function of individual characteristics, such as education, income level, size of the lot, and size of the house, but also might depend on external variable such as temperature and water price (House-Peters and Chang 2011). During droughts, utilities might increase the price of water or impose outdoor water use restriction, and households are forced to change its water use pattern. The aggregation of all consumer decisions defines the total amount of water to be supplied in the system. The reduction of demand can improve the level of water supply sources. Based on the water availability, decision-makers can then modify the restrictions on water demand reduction, which provide feedback into the households' consumptions. Also in the lot level, resident's decisions about land development patterns and levels of imperviousness can alter the long term hydrologic regime, which can impact water availability in a watershed scale. Water scarcity situations, which can be caused by urban pollution, force land planners to impose land development restrictions, such as land zoning, to regulate many impacts of urbanization, including impacts on water resources.

To simulate some of the dynamics described in an urban water system, a CAS modeling framework was developed (Giacomoni et al. 2011). The CAS framework simulates dynamic interactions among land use change, population growth, household water consumption, hydrologic cycle, and reservoir operation and is used to illustrate the impact of decentralized decisions of individual residents and their effects on system-wide sustainability. The CAS schematic is represented in Figure 9 and each component described in more detail in the following sections.

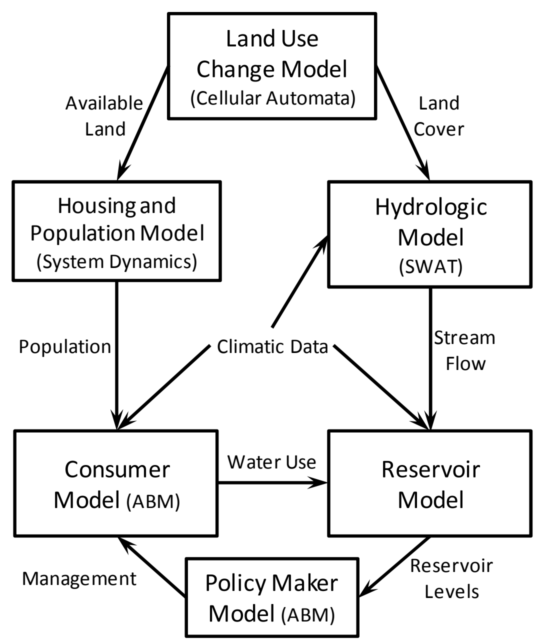


Figure 9. Diagram of the urban water complex adaptive system framework.

Cellular Automata Land Use Change Model

A cellular automata modeling technique (Wolfram 1983) is used to represent the conversion of non-urban land covers to residential areas. In a CA simulation, the landscape is represented as a grid of cells where the state of each cell is updated at each time step based on a transition rule that is a function of the state itself and its neighbors in the previous time step. The transition rule calculates the likelihood that a cell will change state from undeveloped to urban land cover as a function of a weighted average of the number of developed neighbors, distances to main roads, minor roads, central areas, and a random variable. When the likelihood of an undeveloped cell is greater or equal than a development threshold, the cell changes state to urban. If the likelihood is less than the threshold value, the land cover type of the cell remains not urban, and the cell is reevaluated in the next time step.

Population Growth System Dynamics and Housing Model

A system dynamics population growth model (Alfeld and Graham 1976) is adapted to represent the growth of housing and population growth inside a city. The model uses the concepts of stocks and flows to compute the increase of the population, based on the birth, death, immigration and emigration rates. The rate of births, death and emigration is exponential, and a function of fertility, average lifespan, and normalized emigration parameters, respectively. The immigration growth depends on the attractiveness of housing, which is calculated based on the cellular automata land use change model. The cellular automata model calculates the availability of land within the city boundaries, and this information is used to compute the density of new development (e.g., the number of persons in a household) and the number of new houses. The attractiveness of housing is computed based on an adjusted curve of the number of houses divided by the total number of households. The number of households is comprised of the total population divided by the average household size.

Agent-Based Residential Water Demand Model

An agent-based residential water model (Kanta and Zechman 2011) is incorporated in the CAS framework as a model component to simulate indoor and outdoor water demands in a monthly time step. This component stochastically generates a series of monthly water demand levels for a household based on three categories, defined based upon the lot sizes. Category 1 households have a small lot size and do not have gardens, consuming water only indoor. Category 2 agents have indoor and summer (June to November) outdoor water use. During summer months, half of the stochastic generated demand is assigned as indoor demand, and the outdoor use is calculated using a garden end-use model (Jacobs and Haarhoff 2004) that is based on the size of the lot, climatic inputs and an irrigation efficiency factor, being at the maximum half of the total demand. Category 3 agents have 66 percent of the stochastic-generated demand as indoor use and use outdoor water throughout the year. The outdoor use is calculated using the garden model limited to 34 percent of the total demand of the household. Each agent is then assigned with a value representing lot size, rooftop size and household size, which are stochastically generated based on the observed distribution of the study case (U.S. Department of Housing and Urban Development 2002).

The outdoor use of the agents is adaptively reduced during drought periods. As the system enters in a Drought stage, the outdoor water use restriction is implemented. The current policy imposes restriction on the number of times per week an agent is allowed to use water for irrigation purposes. When the system is at no conversation stage, the irrigation efficiency factor is equal to 2, representing a frequency of five days of irrigation per week. For Drought stages 1, 2 and 3, the irrigation frequency factor is reduced to 1, 0.5, and 0, which represents an outdoor frequency use of two, one and zero days of irrigation per week.

Hydrologic Model

The hydrologic model Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) is also incorporated in the CAS framework and connected to the land use change model to represent the main hydrologic processes with the sprawl of urban areas. SWAT subdivides a watershed into hydrologic response units (HRUs), which are unique combinations of land cover, soil type and class of slope, and subwatersheds based on topography. Vertical water balance is computed for the HRUs, and excess water is routed through channels that are assumed to have trapezoidal cross-sections. Within each subwatershed, the fractions of urban and non-urban HRUs are updated in a yearly time step, as the land use change occurs.

Reservoir Model

A reservoir modeling component simulates the main inflows and outflows of a reservoir (Eq.12):

$$\frac{dS}{dt} = SF + DR + IBT - D - LE - R - Sp \tag{12}$$

Inflows to the reservoir are streamflow (*SF*), direct rainfall (*DR*), and inter-basin transfers (*IBT*), and outflows include withdrawal of consumer demands (*D*), lake evaporation (L*E*), release (*R*), and spills (*Sp*).

Agent-based Policy Maker Model

A single agent-based policy maker is implemented within the CAS framework. The policy agent receives the reservoir storage information at a monthly time step and sets the rules to be implemented in each of the other components. Five adaptive management strategies are implemented within the Policy-Maker model. The first two strategies are developed based on existing water use restrictions, typically found in drought contingency plans. The third strategy tests supply augmentation by rainwater harvesting systems, and the fourth strategy relies on demand control by increasing higher density development. The final scenario is a combination of the previous four strategies.

Outdoor Restriction Strategy

The Outdoor Restriction Strategy is an adaptive management policy that is based on the city of Arlington's current drought contingency and emergency water management plan (City of Arlington 2008), which restricts outdoor water use during droughts. The level of restriction is implemented in three stages (Table 1).

Stage 1 - Water Watch

Stage 1 is triggered when the Lake Arlington reservoir storage drops below 75 % (25% depleted) of the conservation storage. Stage 1 ends when the reservoir storage returns to more than 75% of the conservation storage. During Stage 1, outdoor water irrigation is allowed just twice a week per household. Other restrictions to public, commercial and industrial users are imposed but not included in the model.

Stage 2 - Water Warning

Stage 2 is initiated when Lake Arlington drops below 60% (40% depleted) of the conservation storage, and it ends when the reservoir is above the upper limit (75%). The allowed outdoor irrigation frequency is just once a week.

Stage 3 - Water Emergency

The system enters in the emergency stage when the reservoir storage falls below 45% (55% depleted) of the conservation storage. In this stage, there is a total ban of outdoor water use.

Table 1. Outdoor Restriction Strategy stages, triggers and measures.

Stages	Initial and End Trigger[1]	Measures
1 – Water Watch	< 75%	Irrigation twice a week
2 – Water Warning	< 60%	Irrigation once a week
3 – Water Emergency	< 45%	Ban of irrigation

[1] Percentage of conservation storage

Reverse Triggers/Target Reduction Strategy

The Reverse Triggers/Target Reduction Strategy scenario represents a more rigorous drought management plan than the Outdoor Restriction Strategy. It introduces reverse triggers and individual target reductions for all households (Table 2). In this strategy, the triggers that initiate and end a drought stage are not the same.

Stage 1 – Water Watch

Stage 1 is initiated when the reservoir storage is 75% of the conservation storage (25% depleted), and it only ends when the reservoir is above 100% of the conservation storage. In this stage, all households are expected to achieve at least 5% water use reduction. Water users that have outdoor irrigation (Category 2 and 3) should reduce the frequency of outdoor irrigation to twice a week. If outdoor savings is lower than 5% of total individual demand, the difference between the outdoor savings and the 5% target is imposed on indoor use. For households with no outdoor use (Category 1), a target reduction of 5% is applied for indoor use.

Stage 2 – Water Warning

Stage 2 begins when reservoir storage falls to 60% of the conservation storage and ends when storage returns above 75% of conservation storage. At this stage, the target reduction goal is 10% of individual demand. Category 2 and 3 users must achieve water reductions by irrigating only once a week or also reducing indoor use, until the 10% target is met. Category 1 users automatically reduce indoor demand by 10%.

Stage 3 – Water Emergency

The last stage imposes an outdoor water ban and enforces an individual water reduction target of 20%. Category 1 agents must reduce indoor demands, while Category 2 and 3 achieve the target by either outdoor restriction or indoor water reduction. The trigger and reverse trigger of Stage 3 are 45% and 60% of the conservation storage, respectively.

Table 2. Reverse Triggers Strategy stages, triggers and measures.

Stages	Initial Trigger	Reverse Trigger	Measures	
			Category 1	Category 2 and 3
1 – Water Watch	< 75%	≥ 85%	• 5% indoor target reduction;	• mandatory irrigation frequency of twice a week; and/or • 5% total demand reduction;
2 – Water Warning	< 60%	≥ 75%	• 10% indoor target reduction;	• mandatory irrigation frequency of once a week; and/or • 10% total demand reduction;
3 – Water Emergency	< 45%	≥ 60%	• 20% indoor target reduction;	• Ban of irrigation; and/or • 20% total demand reduction;

Development Density Strategy

The Development Density Strategy represents a policy that encourages the construction of higher density developments, represented by agent costumer type 1, and dis-incentivizes building low density areas that tend to consume more water (represented in the model by agents type 2 and 3). The policy adaptively increases the number of permits for consumer type 1 households and decreases the permits for consumer type 2 and 3 households, according to the drought contingency stages (Table 3). The actual distribution of Class 1, 2, and 3 costumers is 12%, 41%, and 47%, respectively. If the system enters drought contingency stage 1, permitting restrictions change the distribution to 70%, 15%, and 15%. The Development Density Strategy also incorporates the reverse triggers and outdoor restrictions used in the Reverse Triggers/Target Reduction Strategy, but not the target reductions.

Table 3. Development Density Strategy scenario stages and percentages.

Stages	% of Consumers		
	Class 1	Class 2	Class 3
0	12	41	47
1	70	15	15
2	80	10	10
3	90	5	5

Rainwater Harvesting Strategy

The Rainwater Harvesting Strategy simulates a rebate program for implementing rainwater harvesting systems in households. This strategy shows the number of rainwater harvesting systems installed in type 2 and 3 households in during the 50 year simulation period. Initially, there are 100 rebates per month, equally divided between agents type 2 and 3. As the system enters a drought, the number of rebates offered each month doubles. For example, if the system enters Stage 1, the number of rebates increases to 200 rebates per month (Table 4).

Table 4. Rainwater Harvesting Strategy stages and number of rebates.

Stages	Number of rainwater harvesting rebates		
	Class 1	Class 2	Class 3
0	0	50	50
1	0	100	100
2	0	200	200
3	0	400	400

It is assumed that agents class 2 and 3 adopt fixed rain barrel volumes of 5.7 cubic meters (1,500 gallons) and 11.4 cubic meters (3,000 gallons), respectively. These values were selected based on reliability study conducted according to methodology described in the Texas Manual on Rainwater Harvesting (TWDB 2005). Over a 50 year period, the storage of the barrels is simulated. The outdoor water use is computed by the consumer agent-based model. The supply of the system is calculated, according to the equation:

$$S = 1000 \times R \times A \times C \tag{13}$$

where: S is the supply (m^3/month), R is the monthly rainfall (mm), A is the roof area (m^2), and C is the runoff coefficient (assumed to be equal to 0.95). For both rainwater harvesting systems, the average reliability is 65%, which means that 65% of the time, the barrels have enough water to supply outdoor demands.

Combined Strategy

The last scenario combines all previous measures in the Reverse Triggers/Target Reduction, Development Density, and Rainwater Harvesting strategies.

Illustrative Case Study

The City of Arlington is used as an illustrative case study. Water conservation and drought management are important practices for urban water systems, especially for systems similar to Arlington, which serves a large and growing metropolitan area located in a semi-arid regions. The city of Arlington, part of the Dallas/Forth Worth Metropolitan region, has a population of approximately 390,000 inhabitants and is projected to grow to 472,000 inhabitants by 2060 (Freese and Nichols et al. 2010). More than half of Arlington's water demand is supplied from Lake Arlington (49.6 million cubic meters at conservation pool elevation), which receives contributions from Village Creek watershed (370 sq. km) and inter-basin transfers provided by the Tarrant Regional Water District (TWRD) from the reservoirs Cedar Creek (795 million cubic meters of conservation storage) and Richland-Chambers (1,372 million cubic meters of conservation storage). These reservoirs, located southeast of Arlington in the Trinity River watershed, have a combined permitted supply of 474 million cubic meters per year (TRWD 2009).

Simulation Scenarios

A projected simulation period of 50 years, from 2010 to 2060, is used to simulate the city's urbanization and population growth. Two sets of rainfall and temperatures time series were selected. The first is a historic time series of rainfall and temperatures taken at climatic stations between 1950 and 2000 (COOPID 411800). During this period, the northeast portion of Texas (climatologic region 3) suffered from several drought events. The drought of record lasts from December 1950 to April 1957.

The second time series of rainfall data uses a set of downscaled rainfall and temperature projections generated by the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) (Maurer et al. 2007). Monthly rainfall and temperature data from 36 scenarios generated by 16 different Global Circulation Models (GCMs) for the greenhouse emission path A2 were selected and analyzed. The emission path A2 assumes a heterogeneous world, with diverse economic regions, increasing global population, and fragmented technological change (IPCC 2000). The Model for Interdisciplinary Research on Climate (MIROC3.2 medres 3) was selected because it generated the lowest annual average precipitation (85% of the historic annual precipitation in the same period). The intention of selecting a the worst-case scenario is to provide an assessment of the performance of the system during a period of low water availability and to test the extent to which adaptive demand management can contribute to improving the system's performance in stressed conditions. Figure 10 shows the monthly average precipitation, maximum and minimum temperatures for the historic and future periods. According to the projections of the selected GCM, the wettest month of the year shifts from May to October, and the warmest month shifts from July to August. With the exception of April and October, there is a decrease in the average amount of precipitation for all the other months.

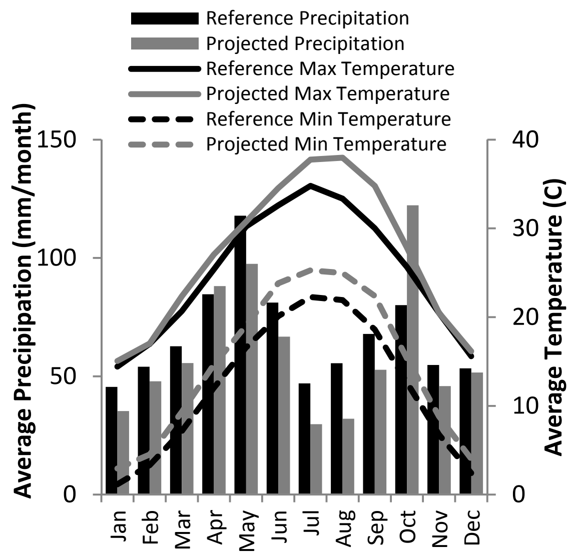


Figure 10. Monthly average precipitation, maximum and minimum temperature for the reference period (1950 – 2000) and projected period (2010 and 2060).

Both rainfall and temperature time series were temporally downscaled from monthly to daily time step based on the relative change factor (CF_{rel}) and absolute change factor (CF_{abs}) (Sunyer et al. 2010). The change factor represents the relationship between a reference period and the projected period. The reference period time for the rainfall and temperature series uses historic recordings, beginning in 1950 and ends in 2000, and the projected period is from 2010 to 2060.

$$CF_{rel} = \frac{R_{month}^{projected}}{R_{month}^{reference}} \tag{14}$$

$$CF_{abs} = T_{month}^{projected} - T_{month}^{reference} \tag{15}$$

where $R_{month}^{projected}$ is the monthly amount of rainfall projected by the GCM, and $R_{month}^{reference}$ is the observed monthly rainfall, $T_{month}^{projected}$ is the monthly average temperature projected by the GCM, and $T_{month}^{reference}$ is the monthly average temperature observed. If no rain occurs in a certain month of the reference period, the change factor is computed using the monthly rainfall of three months window period (previous, the month in consideration, and the subsequent month).

The projected daily rainfall ($R_{day}^{projected}$) and temperatures ($T_{day}^{projected}$) are computed according to the Equations 4 and 5, respectively:

$$R_{day}^{projected} = R_{day}^{reference} \times CF_{rel} \tag{16}$$

$$T_{day}^{projected} = T_{day}^{reference} + CF_{abs} \tag{17}$$

where $R_{day}^{reference}$ is the observed rainfall in a certain day, and $T_{day}^{reference}$ is the observed daily temperature.

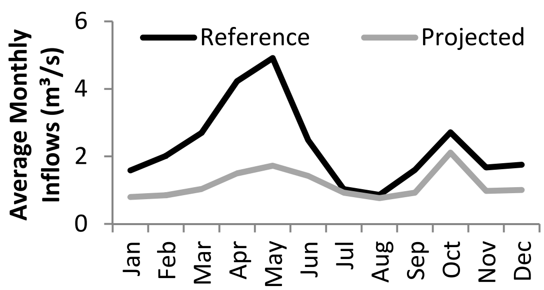
Results

The results are separated based on the interactions between the supply, demands and reservoir dynamics. First, an analysis of the inflows on the Reference and Projected scenarios is performed. Although the system relies strongly on inter-basin transfers, hydro-climatic forces and watershed yields play important roles. Secondly, an analysis of indoor and outdoor water uses is conducted. The improvements produced in each of the scenarios are presented and compared to the Outdoor Restriction Strategy, which is considered the base case. Finally, the gains of each of the tested strategies are shown for the variables reservoir storage, pumping volumes, and spill.

Reference versus Projected Inflows

A substantial difference in inflows exists between the Reference and Projected scenarios. The average monthly inflows and flow duration curve are presented in Figure 11. The average monthly inflows sequence (Figure 11 (a)) shows the wettest month changes from May to October. The average inflows for the future period are lower than the historic period, even though the average precipitation of October for the future scenario is higher than for the historic period. The flow duration curve (Figure 11 (b)) shows a substantial decrease of the high flows, but an increase in low flows with a higher probability of exceedance of 60%.

(a)



(b)

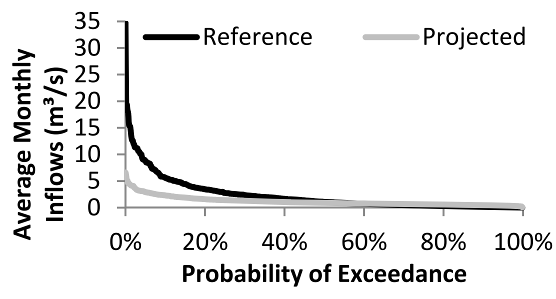


Figure 11. Average monthly inflows (a), and flow duration curves (b) for the reference (1950 – 2000) and projected (2010 - 2060) periods.

Domestic Water Use

One of the most important indicators used to assess the effectiveness of water conservation plans is the daily water per capita consumption. This value represents on average the amount of water consumed by one individual in one day within the water system and is calculated by dividing the total amount of water pumped or diverted for treatment by the total population served. Figure 12 shows the daily water per capita consumption during the 50-year period for the reference (a) and projected (b) simulations. In the first year of the reference simulation, all the Strategies have a daily water per capita use of approximately 442 liters/person/day. As the simulation proceeds during the next 30 years, the daily water usage varies between 374 and 449 liters/person/day for the base case scenario (Outdoor Restriction Strategy). During the final 20 years of simulation, individual water consumption decreases significantly, as the reservoir becomes depleted due to population growth, and outdoor water demands cannot be met. The unsustainable growth causes the reservoir to drop and forces the implementation of outdoor use restrictions permanently. In the projected period, the reduction of daily per capita water use occurs immediately, as the low inflows (compared to the reference time series) cannot sustain the demands of the population or the increase in population. The average daily per capita consumption for the reference and projected simulation under the Outdoor Restriction Strategy is 404 and 376 liters/person/day, respectively.

The Reverse Triggers/Target Reduction, Development Density and Rainwater Harvesting strategies reduce the individual water uses more than the Outdoor Restriction strategy for both analysis periods (Figure 11). The Development Density Strategy reduces water consumption by increasing the number of type 1 households and consequently, decreasing the number of type 2 and type 3 households. At the beginning of the simulation, type 1 households represent 12% of the total households, increasing up to 20% for the reference simulation and to 28% for the projected simulation (Figure 13). The Rainwater Harvesting Strategy manages demands through installation of approximately 160,000 and 170,000 rainwater harvesting systems for the reference and projected simulations at approximately 81% and 88% of the households (Figure 14). For the reference simulation, the implementation rate can be divided in three periods: the first eight years, which represents the drought of records, has a rate of implementation of approximately 3000 rainwater harvesting systems per year; a second period that lasts for approximately 27 years and has on average 2750 rainwater harvesting systems offered each year; and the last 15 years, when demands cannot be sustained and deplete the reservoir, the Policy-Maker initiates very restrictive water conservation measures and offers 6000 rainwater harvesting systems per year. For the projected simulation, two distinct rates of rebate implementation are identified: the first 28 years, when on average, 5700 rainwater harvesting systems are installed per year; and the remaining time, when the number of rebates installed equals the growth of the population because all existing households of type 2 and 3 had adopted the systems. The difference between the reference and projected simulations occurs because in the projected period the system is under stress at the beginning of the simulation, and there is a high frequency of

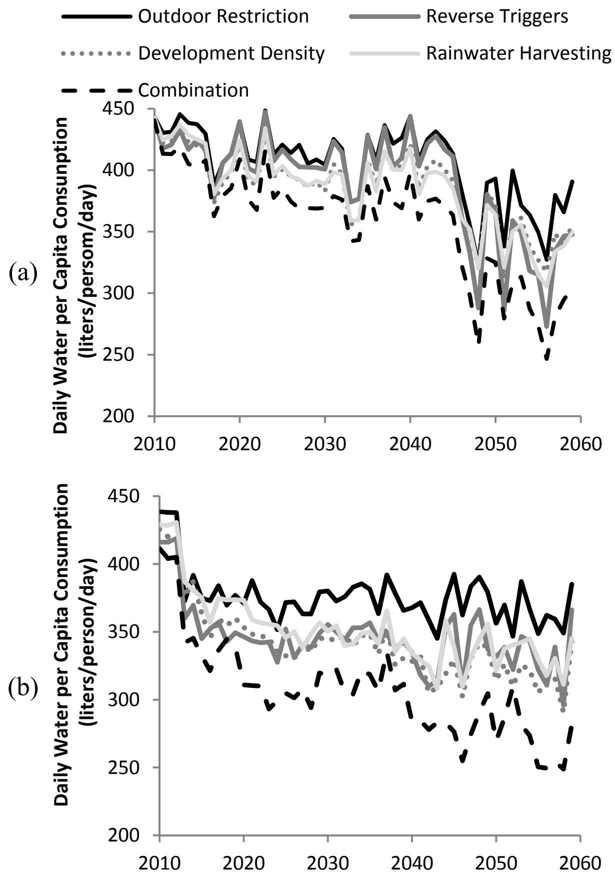


Figure 12. Individual daily water per capita consumption (liters/person/day) for the Reverse Triggers/Target Reduction, Development Density, Rainwater Harvesting, and Combination scenarios in comparison to the Outdoor Restriction for the reference (1950 – 2000) and projected (2010 and 2060) periods.

restrictive drought measures (stage 3), which increases the rate of implementation of rainwater harvesting systems.

The Combination Strategy aggregates the impacts on demand reduction of all strategies and stabilizes water supply most effectively than the separated strategies. For example, during the last five years, the average daily water per capita consumption for the Combination scenario for the reference simulation is 247 liters/person/day, which represents a decrease of 25% compared to the Outdoor Restriction alone. For the projected period, the decrease is almost 30%. Table 5 shows the first and the last five years of average daily water per capita consumption (liters/person/day) for the reference and projected simulations and percentage reductions for the tested strategies in comparison to the Outdoor Restriction strategy. These results indicate that the per capita daily water consumption can decrease via two pathways. Because of population growth, there is an increase of the restriction frequency over time, impacting the daily per capita demand. The second way that demands are decreased is through the long-term measures (Development Density and Rainwater Harvesting strategies) that reduce water consumption permanently.

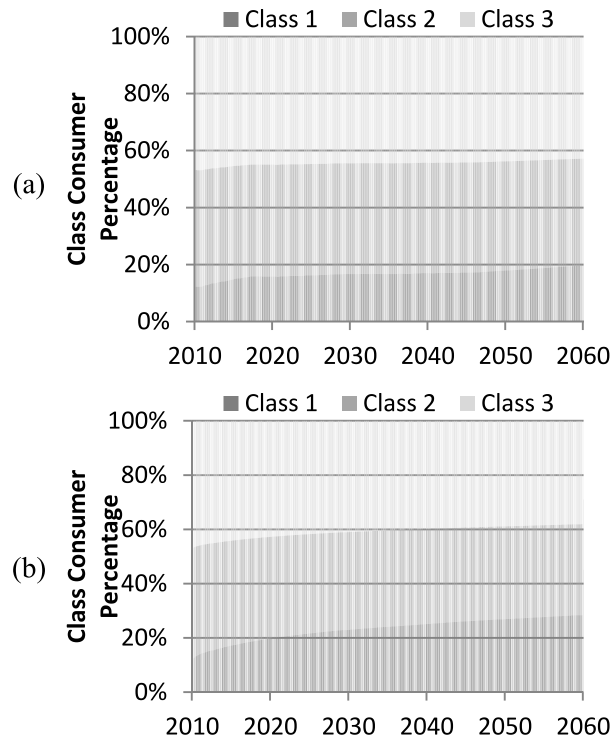


Figure 13. Percent change of consumer classes for the Development Density scenario for the historic (a) and future (b) periods.

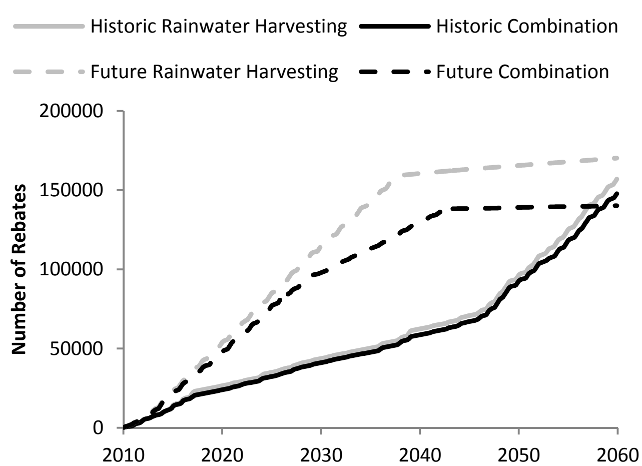


Figure 14. Number of rebates implemented in the Rainwater Harvesting and the Combination scenarios for the historic (a) and future (b) periods.

Table 5. Five years average daily water per capita consumption (liters/person/day) and percentage reductions for the tested strategies.

Strategy	Historic			Future		
	First 5 years	Last 5 Year	% Gains from the base case	First 5 years	Last 5 Year	% Gains from the base case
Outdoor Restriction (Base Case)	426	327	-	416	349	-
Reverse Triggers/Target Reduction	415	273	17%	396	296	15%
Development Density	418	317	3%	405	291	17%
Rainwater Harvesting	421	305	7%	411	311	11%
Combination	407	247	25%	382	249	29%

Average monthly indoor and outdoor water uses are depicted in Figure 15 (a) and (b), respectively, for both the reference (left column) and projected simulations (right column). On average, for the Outdoor Restriction Strategy, the indoor demands are 50 million m^3 per year for the historic simulation, and 48 million m^3 per year in the future simulation, with maximum and minimum water use occurring in the months of December and November, respectively. The Reverse Triggers, Development Density and Combination strategies are able to reduce indoor demands for all the months of the year in comparison to the Outdoor Restriction Strategy, because the target reductions mechanism and the decrease of number of type 2 and 3 households. The system consumes around 17.2 million m^3 for outdoor activities in the reference simulation and 12.6 million m^3 in the projected simulation. As opposed to the indoor demands that are relatively constant throughout the year, the outdoor demands fall in the winter months and increase substantially in the summer months due to high temperatures of the area. The Development Density and Rainwater Harvesting strategies are more effective in reducing outdoor demands than the Reverse Triggers/Target Reduction Strategy, especially for the months of June, July and August. The Rainwater Harvesting Strategy is able to reduce substantially the amount of water needed for outdoor use in the winter months, but it is able to reduce only a small percentage of outdoor water demands during the summer.

Figure 16 shows the percent changes for indoor, outdoor and total water uses of the Reverse Triggers/Target Reduction, Development Density, Rainwater Harvesting, and Combination scenarios in comparison to the Outdoor Restriction for the reference and projected periods. Under reference scenario, the Reverse Triggers/Target Reduction, Development Density and Combination strategies decrease indoor water uses by 4.9%, 4.4%, and 8.2%, respectively. Under projected hydro-climatic conditions, these strategies are even more efficient, reducing indoor demands by 12.6%, 10.8%, and 17.1%, respectively (Figure 16 (a)). The indoor uses of the Rainwater Harvesting scenario are the same as the base case, as the water collected in the barrels is used only to supply outdoor demands.

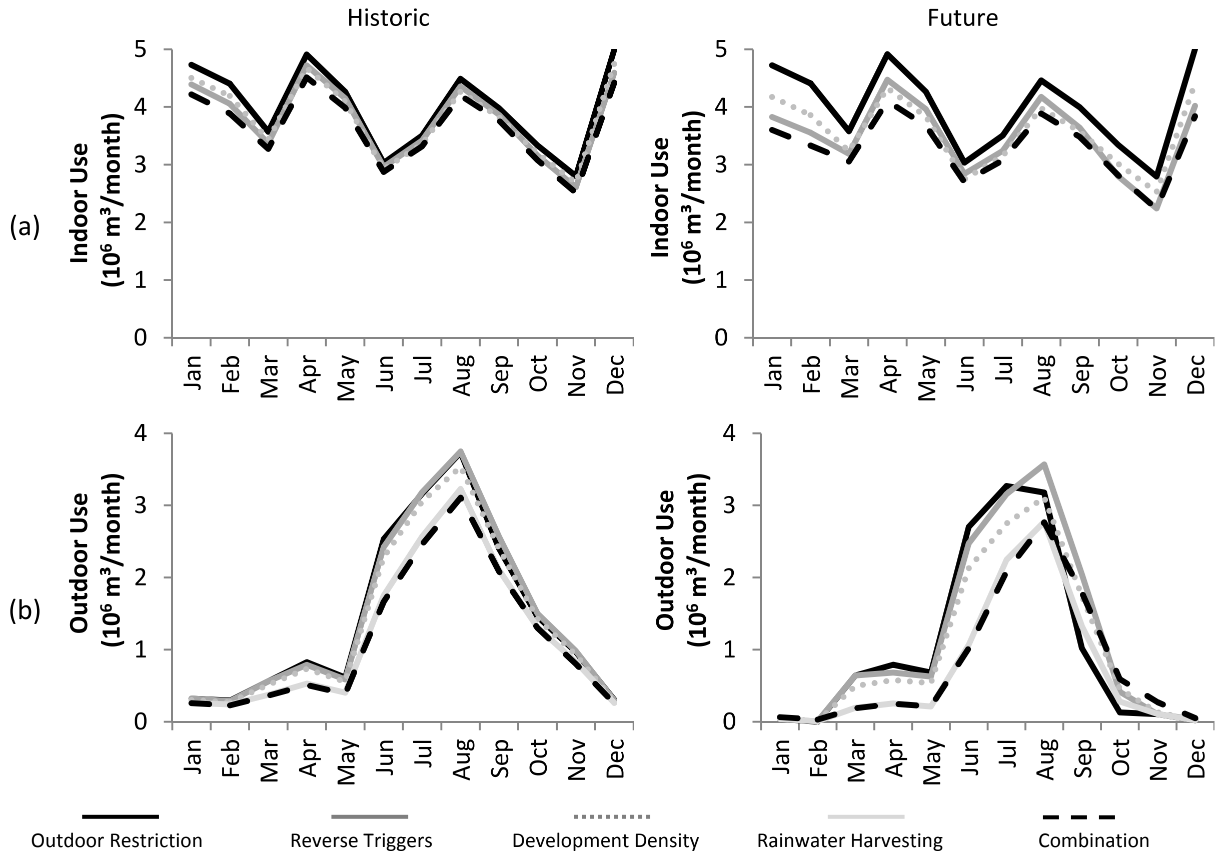


Figure 15. Average monthly indoor (a) and outdoor uses (b), for the Outdoor Restriction, Reverse Triggers, Development Density, Rainwater Harvesting, and Combination strategies for the reference (left column) and projected (right column) periods.

(a)

(b)

(c)

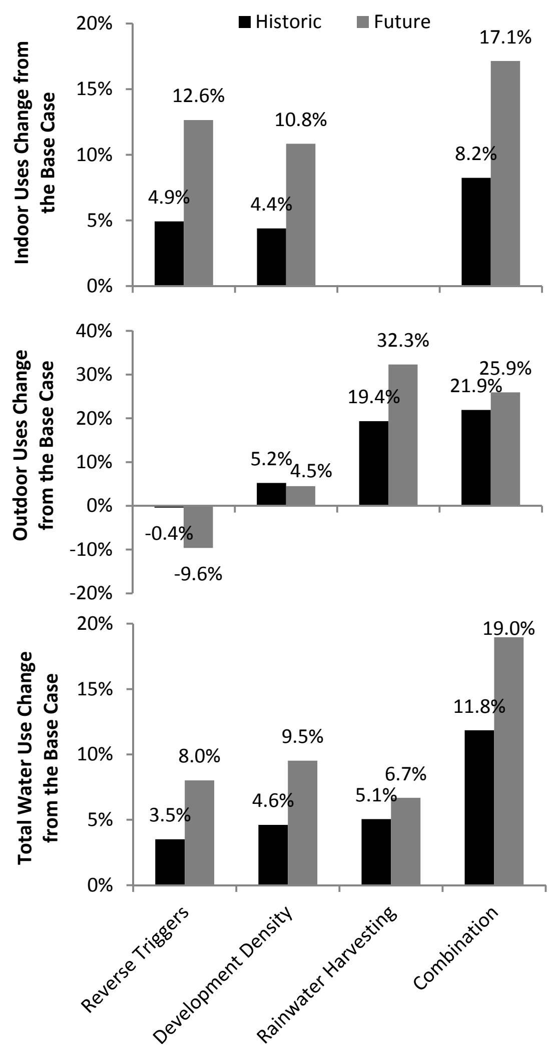


Figure 16. Indoor (a), outdoor (b), and total (c) water use percent change for the Reverse Triggers, Development Density, Rainwater Harvesting, and Combination scenarios in comparison to the Outdoor Restriction for the historic (1950 – 2000) and future (2010 and 2060) periods.

The Development Density, Rainwater Harvesting and Combination scenarios reduce outdoor water use for the reference and the projected periods, while the Reverse Triggers scenario shows an increase of outdoor water use. For the Development Density scenario, the decrease of outdoor water use occurs due to the decrease of type 2 and 3 households and increase of type 1 households, which has no outdoor usage. The Rainwater Harvesting scenario reduces outdoor water use that is supplied by the system because rainwater is used as an alternative supply for outdoor purposes. The Combination scenario maximizes the reduction of outdoor use, by combining the mechanisms of Development Density and Rainwater Harvesting. Under the Reverse Triggers/Target Reduction Strategy there is an increase of outdoor water use. Although the system remains in one of the demand restriction stages for longer periods than the Outdoor Restriction scenario (51% of the time for the reference period, and 39% of the time for the projected period, respectively), the outdoor demand savings in the Reverse Triggers Strategy is lower because it remains in the most restrictive stage (water emergency) relatively shorter time.

In terms of total water use reductions, the Reverse Triggers, Development Density, and Rainwater Harvesting strategies have similar outcomes (3.5%, 4.6%, and 5.1% improvements for reference scenario, and 8.0%, 9.5%, and 6.7% for the projected simulation). Combining target reductions, reverse triggers, density change, and rainwater harvesting systems achieves the highest demand reduction of 11.8% and 19% in the reference and projected simulations, respectively (Figure 16 (c)). This result is expected as each mechanism adds to reducing water usage.

Reservoir Storage, Inter-basins Transfers, and Spills

All adaptive demand management strategies are able to increase the long-term average reservoir storage (Figure 17 (a)). For the reference simulation, the reservoir storage increases on average 1.2%, 1.3%, 1.8%, and 4.1%, for Reverse Triggers, Development Density, Rainwater Harvesting, and Combination scenarios, respectively. For the projected simulation, the gains are more substantial: 10%, 11%, 7%, and 39%, respectively. The effectiveness of the strategies for the projected simulation is higher than the historic simulation because of the lower water availability that depletes the reservoir storage, forcing the system to remain for longer periods under water use restrictions.

The savings obtained by the water demand management strategies are able to reduce the amount of inter-basin transfer volumes. For the reference simulation, there is a reduction of 1.0%, 2.6%, 2.6%, and 5.4% of the pumping volumes for the Reverse Triggers, Development Density, Rainwater Harvesting, and Combination scenarios, respectively. For the projected simulation, as the system is permanently constrained by low inflows, the pumping volumes are higher than the historic simulation, and the adaptive strategies introduce small changes in the pumping dynamics (Figure 17 (b)).

Because the adaptive water demand strategies increase reservoir storage, the losses due to high flows through the emergency spill way increase (Figure 17 (c)). For the reference simulation, there is an increase of 0.2%, 1.7%, 1.6%, and 3.4% for the Reverse Triggers, Development Density, Rainwater Harvesting, and Combination scenarios, respectively. In the projected simulation, however, there is no occurrence of losses through the spill way in any of the scenarios due to the lower inflows into the reservoir. The substantial reduction of high inflows is caused by the decrease of projected rainfall that impact runoff generation, and also by the increase of evapotranspiration due to a warmer climate.

(a)

(b)

(c)

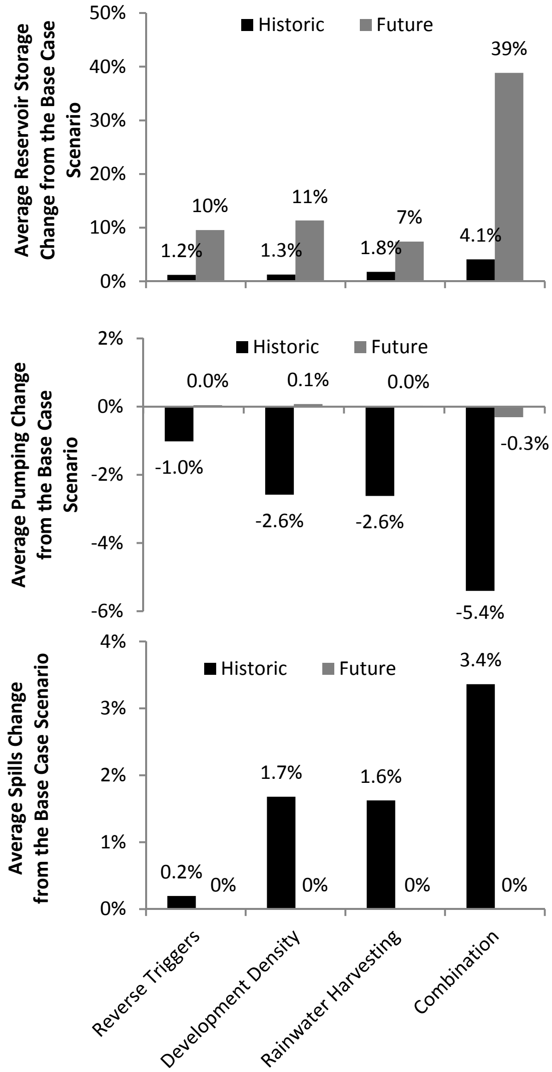


Figure 17. Average reservoir storage (a), average pumping volume (b), and average spill volume (c) percent change for the Reverse Triggers, Development Density, Rainwater Harvesting, and Combination scenarios in comparison to the Outdoor Restriction strategy for the historic (1950 – 2000) and future (2010 and 2060) periods.

Discussion

Overall analysis of the results indicates that adaptive demand management strategies can help water systems cope with increasing stresses of population growth, droughts and potential decrease of water availability due to climate change. Because the implementation of drought contingency/conservation actions is tied to water availability of the system in a specific time, the efficiency of the adaptive management results from the level of stress the system is submitted. If the system is submitted to a decrease of water availability caused by climate change for example, than the intensity and frequency of the actions taken to alleviate low water availability conditions increase. This is illustrated by the results found in this study, where the performance of the adaptive strategies under the future scenario is higher than the historic period. In an opposite direction, if the system has enough inflows to maintain water availability levels above the required demands, the adaptive demand management will be enacted very infrequently, which reduces the strategy efficiency. This feedback mechanism helps the system to balance supply and demand sides.

The results presented here are difficult to compare to real indicators of the Arlington system because of simplifications adopted in the models (e.g. the reservoir levels used to trigger drought stages consider the overall storage capacity and not only Lake Arlington), but they show potential gains that adaptive demand management strategies can bring to stressed urban water systems. It is shown, as expected, that the combination of all the strategies reduces total water consumption the most, followed by the Development Density Strategy, Reverse Trigger/Target Reduction, and Rainwater harvesting strategy. These results have some implications for future water management planning. The implementation of individual water target reductions for households during drought periods has positive impacts on total water use, including reductions on indoor usage. Target reductions for individual households have the benefit of sharing responsibility among all users of the necessity of conserve water, especially during severe droughts. Monthly and annual individual water budget and target reductions can be included in water bills, helping to increase awareness among residents about the challenges that population growth, droughts and climate change cause to water supply systems. Rainwater harvesting systems can also benefit the water supply for long-term considerations, as well as for controlling the excess of stormwater generated by imperviousness in urban areas.

The CAS framework provides a method to assess the interactions among different conservation measures and management practices. The results show that the benefit on water reduction obtained by the Combined Strategy is not the direct sum of the individual benefits of the other strategies separately. There is a dynamic interaction among the strategies. For example, when Development Density increases the number of household type 1 that represents residents living in apartment buildings there are less potential residents willing to install rainwater harvesting systems. In the system level, water use reductions obtained by one strategy changes the frequency of measures in the future, impacting the overall efficiency of the system and potentially increasing outdoor water use, as the results for the Reverse Trigger/Target Reduction Strategy show (Figure 16 (b)). The results also show the performance of the strategies for short- and long-term impacts. For example, under reference scenario, the least effective strategy in terms of daily per capita water use in the first five year period is the Rainwater Harvesting. This occurs because the simulation initiates with the drought of record, and rainwater harvesting performs poorly during droughts. For the last five-year period, however, the least effective strategy in terms of daily per capita water demand under historic conditions is the Development Density Strategy. The results of the reference 50-year period show that Rainwater Harvesting Strategy outperforms all other solitary strategies with respect to total water use (with the exception of the Combined Strategy), but it is outperformed by the Development Density Strategy and Reverse Trigger/Target Reduction strategies for the projected period, indicating that the climatic regime does influence adaptive management strategy. For wetter locations, rainwater harvesting technologies have advantages over the other tested strategies. For drier scenarios, other strategies might be recommended, and land use planning can have significant influence in the future ability of water supply systems to meet demands.

Summary and Conclusions

This study applied a Complex Adaptive Systems modeling framework for simulating long-term adaptive management of water demands in urban areas under climatic and demographic stress. Two simulations and five management scenarios were considered. The reference simulation used observed hydro-climatic data and the projected simulation used a projection of climate change obtained from a GCM. The adaptive water demand management scenarios tested were the Outdoor Restriction, which is based on current drought contingency plan and adopts outdoor water restrictions implemented in three drought stages; the Reverse Triggers/Target Reduction Strategy, which incorporate reverse triggers for the definition of drought stages and household target reductions; the Rainwater Harvesting Strategy that represents a plan to augment supply for outdoor purposes; and the Development Density Strategy that prioritizes the construction of high density developments over low density neighborhoods. Increasing population density can have other potential benefits for water management in the watershed scale, and more research is necessary to account its impacts.

The results indicate that each of the tested strategies contributes to household outdoor and indoor water use reduction. The combination of the different water conservation mechanisms resulted in significant levels of demand reduction, increase of reservoir storage levels, and decrease of inter-basin transfers. The future climate change scenario shows an unsustainable amount of water availability in comparison to the historic levels. The uncertainties of long term climate change projections are difficult to assess, and the results for the future simulation scenario can be considered as a worst case reference scenario. The levels of implementation of the adaptive management strategies used in this study were defined based on current and existing practices. For example, the demand reduction targets, the number of rainwater harvesting rebates, and the percentages of high, medium and low density users were defined, without economic considerations. Future work can couple optimization methodologies with the CAS framework to identify optimal policies for water management to take into account limited resources and objectives of sustainability and economic viability for water utilities.

CHAPTER IV

MULTIOBJECTIVE EVOLUTIONARY OPTIMIZATION OF ADAPTIVE DEMAND MANAGEMENT STRATEGIES FOR AN URBAN WATER RESOURCE SYSTEM

The rise of water use caused by population growth, and the potential increase of frequency and intensity of extreme events such as droughts, threat the ability of urban water systems to sustainably balance supplies and demands. Environmental and financial constraints have changed the water planning paradigm from supply enhancement to water conservation. The present study applies a Complex Adaptive Systems simulation-optimization framework to identify optimal adaptive water demand management strategies and explore conflicting tradeoffs within an urban water system subjected to drought conditions and population growth. Inter-basing transfers, water utility revenue, and frequency of restrictions are the objectives analyzed. Short term strategies that are effective only during drought periods, and long term strategies that enhance the system capacity to control water use in the long term, such as high density developments and rainwater harvesting systems, are tested. Short term strategies, that restrict outdoor water use, have limited capacity to cope with future stresses, and the combination of strategies is recommended to balance the supply and demand side of the water system.

Introduction

Urban water resource systems are threatened by the rise in water consumption caused by rapid population growth and urbanization. Climate change is also identified as a potential threat to water resources (Roy et al. 2012) as it may increase the variability of climate and exacerbate the frequency and severity of extreme events, such as droughts. Significant adverse effects are expected for large metropolitan areas in arid and semi-arid regions that recurrently suffer from drought conditions. To decrease the probability of water shortages and alleviate the tension of supply and demand, both water supply management and demand management options are available for water utilities. Supply management includes inter-basin transfers that convey large volumes of water from distant sources to the center of urban consumption. Demand management includes, for example, water use restrictions that are enacted during water shortages.

The historic water resources management paradigm typically treats the problem of increasing water demand through supply augmentation, ensuring that the reliability of the system remains higher than an acceptable risk (de Loe et al. 2001; Inman and Jeffrey 2006). Financial and environmental constraints, however, have changed this paradigm of management, and today, demand management is essential to ensure that the water resource supply system can sustainably meet present and future demands. To achieve this goal more efficiently, water conservation strategies that typically have long term impacts, and drought management strategies that have short term impacts, should be implemented in combination (Wilchfort and Lund 1997), so the water system remains balanced both during low flow periods and over a long-term planning horizon.

Adaptive water demand management is defined here as the dynamic implementation of water conservation or contingency measures. Adaptive management was originally proposed as a systematic and interdisciplinary approach to improve the management of natural resources by promoting adaptation and change (Holling 1978). Waters (1986) incorporated the idea of using dynamic modeling to assess the impact of alternative policies. Giacomoni and Zechman (2012) simulated adaptive water demand management in an urban water system subjected to recurrent cycles of drought using a Complex Adaptive Systems (CAS) approach. Scenarios of water restrictions, decentralized supply augmentation with rainwater harvesting systems, and land use change, were assessed under population growth for historic and projected hydro-climatic conditions. The CAS modeling approach uses modeling techniques including agent-based modeling (ABM), cellular automata (CA) and system dynamics, with watershed and reservoir models, to simulate household water consumption, land use change, population growth, supply side, and water use regulation. Management strategies for adaptive demand management were configured and defined based on rules and values from literature, best practices, and the case study.

This paper couples the CAS simulation framework with an Evolutionary Algorithm (EA) optimization procedure to identify the configuration and the combination of water demand management strategies to better balance existing and future demands and supplies. Since urban water systems are complex and inherently have multiple objectives, a multi-objective evolutionary algorithm (MOEA) was used to identify the trade-offs among inter-basin transfer volumes, utility revenue, and the frequency of water use restrictions. Minimization of energy costs for pumping inter-basin transfers conflicts with the reliable delivery of water during droughts and with the reduction of water use restrictions. Adaptive water demand management strategies can increase the reliability of water supply, but can decrease revenues for water utilities. The reduction of water use due to water conservation can reduce the resources required for the operation, maintenance and expansion in the future. Exploring the relationships between inter-basin transfers, utility revenue, and restriction frequency can assist in designing sustainable systems. The CAS-MOEA simulation-optimization framework was applied for the water supply system of Arlington, Texas.

Simulation-Optimization Methodology

A simulation-optimization framework was developed for optimizing adaptive water demand management, by coupling an urban water resources CAS model with a Multi-Objective Evolutionary Algorithm (MOEA) (Figure 18). The CAS modeling framework, originally developed by Giacomoni and Zechman (2012), is composed of seven models: (1) a Consumer Agent-Based Model; (2) a Policy Maker Agent-Based Model; (3) a Reservoir Model; (4) a Population Growth Model; (5) a Housing Growth Model; (6) a Watershed Model; and (7) a Land Use Change Model. The last four components (items 4-7) are not included in the simulation-optimization framework, as the demand management strategies that are simulated and optimized do not alter the population growth and land use change processes. Instead, the total population growth and dynamic change in land use is kept constant among all simulations. Initial inputs for the Consumer ABM Model and Reservoir Model were created using the four components.

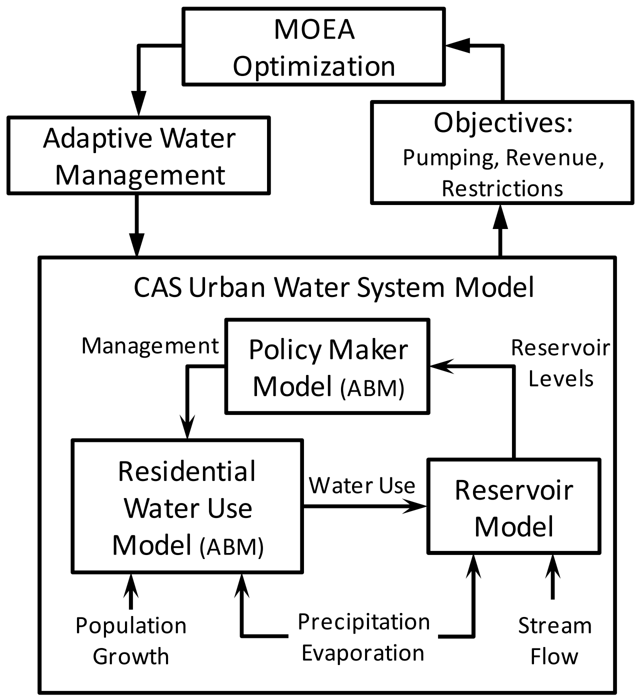


Figure 18. Flowchart of the Simulation-Optimization framework.

Agent-based Residential Water Use Model

An agent-based residential water consumer model (Kanta and Zechman 2011) simulates the indoor and outdoor water use within a household. A gamma distribution function that was fitted based on historic water usage data was used to stochastically generate total water demands for each month of the year for each agent. There are three types of agent consumers, and the separation between indoor and outdoor water use depends on the agent category and the month of the year. Type 1 agents consume water only for indoor purposes. Type 2 agents consume water for indoor purposes throughout the year and outdoor usage only during summer months. During summer months, 50% of the Type 2 agent total demand is allocated to indoor use, and the outdoor demand is computed using a garden end-use model with a maximum amount of 50% of the total agents water use. Type 3 agents have indoor and outdoor water usage during all months of the year. During non-summer months, the indoor usage is equal to 66% of the total water use and the outdoor water use is calculated by the garden end-use model with a limit of 34% of the total demand. During summer months, the outdoor water use is expected to increase, so the total demand is divided in 50% for indoor purposes, and a maximum 50% for outdoor use. The garden end-use model (Jacobs and Haarhoff 2004) takes into account the garden area, vegetation type, rainfall and evaporation variables.

Reservoir Model

A reservoir modeling component simulates the storage, main inflows and outflows of a reservoir (Eq.18):

$$\frac{dS}{dt} = SF + DR + IBT - D - LE - R - Sp \tag{18}$$

where inflows to the reservoir are streamflow (*SF*), direct rainfall (*DR*), and inter-basin transfers (*IBT*), and outflows include withdrawal of consumer demands (*D*), lake evaporation (*LE*), release (*R*), and spills (*Sp*).

The monthly stream flow time series was computed using the watershed model Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998). Measured values of rainfall and pan evaporation were used to estimate direct rainfall (*DR*) and lake evaporation (*LE*), respectively, by multiplying the depth of rainfall and evaporation by the inundated area of the lake. The area of the lake is updated at each time step, function of the storage surface area curve (TWDB 2008).

The inter-basin transfer rule is designed to keep the lake elevations near to a critical path, which is defined by target elevations at each month (Freese and Nichols 1999). The total amount of inter-basin volumes (Eq.19) is the difference between the water demand and the estimated supply (Eq.20) that is based on historic average monthly reservoir inflows and evaporation.

$$IBT = Demand - Supply \tag{19}$$

$$Supply = S - TS + AIn - ALE \tag{20}$$

where S is the current storage, TS is the target storage, AIn is the assumed inflows, and ALE is the assumed lake evaporation.

Agent based Policy Maker Model

A single agent model representing a water policy maker is included in the CAS framework to simulate the implementation of adaptive water demand management strategies. The policy agent receives at each time step the reservoir storage and set the rules for implementing adaptive water demand management, based on the drought stages. In each drought stage, that is defined based on the triggers, the following measures are defined: the level of outdoor water use restriction, the target demands, the number of rainwater harvesting rebates, and the number of permits for the new households. The agent-based policy maker model can implement five different adaptive management strategies. Each strategy is implemented in three drought stages.

Outdoor Restriction Strategy

The first adaptive strategy is called Outdoor Restriction and it represents the existing drought contingency and emergency water management plan for the City of Arlington (City of Arlington 2008). This plan has three drought stages. The first stage, called water watch, is initiated when the reservoir storage in below 75% of the conservation pool storage, and limits outdoor water use to twice a week. The second and third stages are called water warning and water emergency. They initiate when the reservoir storage is below 60% and 45% of the conservation pool storage, respectively, and outdoor water use is limited to once a week and no irrigation, respectively.

Reverse Triggers/Target Reduction Strategy

The second strategy, called Reverse Triggers/Target Reduction Strategy, is also implemented in three stages with the same outdoor restriction measures of the previous strategy. In the Reverse Triggers/Target Reduction strategy the triggers that initiate and end a drought stage are different, and each household has individual target demand reductions. For example, a drought stage 1 would start if the reservoir storage is lower than 75% of the conservation capacity, but will only end when the reservoir storage is above 85% of the conservation pool strategy. This strategy keeps the system in drought stages for longer periods, which can potentially reduce water usage in comparison to the Outdoor Restriction Strategy. In addition to the reverse triggers, target demand reductions are imposed on consumer agents. For example, for drought stages 1, 2, and 3, targets of 5%, 10% and 20%, respectively, of the total demand are enacted. For agent type 1, the target reduction is imposed only for indoor use; agents type 2 and 3 restrict outdoor use by decreasing irrigation. If the restrictions do not meet the target reduction, indoor water use is also decreased until the target demand reduction is met.

Development Density Strategy

Type 1 consumer agents consume less water than Types 2 and 3 consumer agents because they only use water for indoor purposes. The former represent households that live in more dense areas, such as buildings and apartments, where dwellings do not have gardens or lawns. The Development Density Strategy represents a policy that changes the composition of high and low density households, by increasing the number of permits issued to type 1 consumer agents, and decreasing the number of new households for type 2 and 3 agents. The implementation of this policy is adaptive, according to the drought stages that are defined for reverse triggers.

Rainwater Harvesting Strategy

Another adaptive strategy is the implementation of rainwater harvesting systems for outdoor water use. The Rainwater Harvesting Strategy adaptively offers a certain number of rebates per month to type 2 and 3 consumer agents. In a regular period, when no drought stage is initiated, a base number of rebates is offered each month and implemented by households to irrigate lawns and gardens. For increasing drought stages, the number of rebates increases.

Combined Strategy

The last strategy, called Combined Strategy, merges the measures of the Reverse Triggers/Target Reduction, Development Density, and Rainwater Harvesting strategies.

Multi-objective Problem Formulation

The conflicts among three objectives are explored here, to evaluate the performance of water conservation strategies and sustainability of the system. The first objective is to minimize the volume of inter-basin transfers (*IBT*). Reducing dependence on external water resources maintains a healthier aquatic ecosystem for external water resource systems and decreases energy costs. The second objective is the maximization of the present value of the utility revenue (*UR*) (represented mathematically as the minimization of the negative function of utility revenue). The present value of the utility revenue was calculated as the sum of all consumer agent monthly water bills after an annual discount rate. The third objective is minimization of the frequency of water use restriction *(FR)* (Eq. 21). The restriction frequency is calculated as the number of months the system is within any drought stage divided by the total number of time steps (300). The adaptive water demand management strategies (*AWDMS*) as described above are optimized for two multi-objective problems. The first, called here as Model 1 (Eq. 21), is the minimization of inter-basin transfers and maximization of utility revenue. Model 2 (Eq. 22) is the minimization of inter-basin transfers and minimization of restriction frequency. These two models have the following problem formulation:

$$\min f\left(AWDMS\right)=\left[IBT(AWDMS),-UR(AWDMS)\right]^T \tag{21}$$

$$\min f\left(AWDMS\right)=\left[IBT(AWDMS),FR(AWDMS)\right]^T \tag{22}$$

The strategies are Outdoor Restriction (*ORS*), Reverse Triggers/Target Reduction (*RTTRS*), Development Density (*DDS*), Rainwater Harvesting (*RWHS*), and Combined strategy (*COMS*).

Outdoor Restriction Strategy

The Outdoor Restriction strategy has three decision variables (t_1, t_2, t_3), which define the triggers of the drought stages, by percent of conservation pool (Eq. 23).

$$\begin{aligned} &ORS = f\left(t_1, t_2, t_3\right) \\ &0 \leq t_1, t_2, t_3 \leq 1 \end{aligned} \tag{23}$$

where t_1 is the trigger for drought stage 1, t_2 is the trigger for drought stage 2, and t_3 is the trigger for drought stage 3.

Reverse Triggers/Target Reduction Strategy

The Reverse Triggers/Target Reduction Strategy implements the concept of different triggers for initiating and terminating each drought stage and the target reduction values. The first three decision variables sets the value of the reverse triggers (t_1, t_2, t_3), and the second set of variables defines the target reduction values (tr_1, tr_2, tr_3), which can have a maximum value of 10% for drought stage 1, 20% for drought stage 2, and 40% of drought stage 3. The Reverse Triggers/Target Reduction strategy model is represented in Eq. 24:

$$\begin{aligned} &RTTRS = f\left(t_1, t_2, t_3, tr_1, tr_2, tr_3\right) \\ &0 \leq t_1, t_2, t_3 \leq 1; 0 \leq tr_1, tr_2, tr_3 \leq 1 \end{aligned} \tag{24}$$

Development Density Strategy

The Development Density Strategy updates the percentage of new consumer agents that are created at each drought stage. During drought periods, permits for type 1 agents increase and type 2 and 3 agents decrease. When the system exits the drought stages, the number of permits returns to the original values. The first three decision variables represent the reverse triggers of the drought stages (t_1, t_2, t_3) and six following variables represent the percentage of each agent class at each drought stage ($p_{Stage=1,2,3}^{Class=1,2,3}$). The percentage of each agent class at each drought stage is based on a single decision variable that defines the percentages for each household class for drought stage 0. Based on that, the percentages of new type 2 and 3 consumer agents are proportionally decreased.

$$\begin{gathered} DDS = f\left(t_1, t_2, t_3, p_1^1, p_2^1, p_3^1, p_1^2, p_2^2, p_3^2, p_1^3, p_2^3, p_3^3\right) \\ 0 \le t_1, t_2, t_3 \le 1\,;\, 0 \le p_{1,2,3}^{1,2,3} \le 1 \end{gathered} \tag{25}$$

Rainwater Harvesting Strategy

The Rainwater Harvesting Strategy represents a water conservation program that implements at each time step a certain number of rainwater harvesting systems for type 2 and 3 consumer agents. Similar to previous strategies, the first three decision variables (t_1, t_2, t_3) represent the trigger and reverse trigger levels. The next two variables represent the volume of the rain barrel to be adopted by the agents. The maximum and minimum volume for type 2 agents (v_2) and type 3 agents (v_3) is 37.85 and 1.89 m³, respectively. The initial number of rebates (nr_0) can assume a value between the minimum and maximum values of 100 and 200 rebates, respectively. As the system enters a new drought stage, the number of rebates offered doubles. The mathematical formulation of the Rainwater Harvesting strategy is described in the Eq. 26.

$$RWHS = f\left(t_1, t_2, t_3, v^2, v^3, nr_0, nr_1, nr_2, nr_3\right)$$
$$0 \le t_1, t_2, t_3 \le 1 ; 1.89 \le v_{2,3} \le 37.9 \tag{26}$$
$$100 \le nr_0 \le 200; 200 \le nr_1 \le 400; 400 \le nr_2 \le 800; 800 \le nr_3 \le 1600$$

Combined Strategy

The Combined Strategy includes four new decision variables, representing the adoption of the ORS ($aors$), the RTTRS ($arttrs$), the DDS ($adds$), and the RWHS ($arwhs$), respectively (Eq. 27). The new decision variables range from 0 to 1; if their values are less than 0.5, the strategies are enacted; otherwise, the policies are not applied. This procedure allows all combination of strategies. In total, the Combined strategy uses and finds values for 12 decision variables:

$$COMS = f\begin{pmatrix} aors, t_1, t_2, t_3, \\ arttrs, tr_1, tr_2, tr_3, \\ adds, p_1^1, p_2^1, p_3^1, p_1^2, p_2^2, p_3^2, p_1^3, p_2^3, p_3^3, \\ arwhs, v^2, v^3, nr_0, nr_1, nr_2, nr_3 \end{pmatrix} \tag{27}$$
$$0 \le aors, arttrs, adds, arwhs \le 1$$

where *aors* represents the adoption of the Outdoor Restriction Strategy, *arttr* the adoption of Reverse Triggers/Target Reduction Strategy, *adds* the adoption of Development Density Strategy, and *arwhs* the adoption of the Rainwater Harvesting Strategy.

Multi-objective Evolutionary Algorithm

The Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al. 2002) was connected with the CAS simulation framework. NSGA-II is designed to reduce high computational complexity of non-dominated sorting, include an elitism mechanism to preserve non-dominated solutions, and remove the need of special knowledge about the problem to set the parameter for maintaining diversity (sharing parameter). A fast non-dominated sorting approach is included that reduces the computational burden, and a diversity preservation mechanism is based on the concept of crowding density. NSGA-II has been widely used in many engineering fields, including water resources applications. An extensive review of studies that apply MOEAs, including NSGA-II, in water resource planning and management is described by Nicklow et al. (2010).

Case Study

The CAS/MOEA simulation-optimization framework is applied to identify management strategies for the water system of Arlington, Texas. This system supplies water for a population of approximately 390,000 inhabitants, a number projected to grow to 472,000 by 2060 (Freese and Nichols et al. 2010). Approximately half of Arlington's water usage is withdrawn from Lake Arlington (49.6 Mm^3 at conservation pool elevation), which receives inflows from Village Creek (drainage area of 370 km^2) and inter-basin transfers from the reservoirs Cedar Creek and Richland-Chambers. Inter-basin transfers are managed and provided by the Tarrant Regional Water District (TRWD), which delivers raw water to 71 municipalities, including Fort Worth, Mansfield, and Trinity River Authority (TRA), and serves a total population of 1.75 million people (TRWD 2009). The Arlington system is dependent on inter-basin transfer, as Texas has periodically suffered from drought events. The drought of record extended from 1950 to 1957, and the year 2011 was the most intense recorded one-year drought (Nielsen-Gammon 2011).

Arlington Water Utility Department uses an increasing water block rate structure. A household water bill is composed of a fixed monthly fee that is a function of the size of the water meter ($5.00 for a residential user with a ¾" meter and a monthly water use less than 2,000 gallons, and $8.57 for water use higher than 2,000 gallons per month), and a variable charge per additional thousand gallons that is consumed. The residential block structure rate is presented in Table 6.

Table 6. City of Arlington residential block structure rates.

Usage (1000 gallons)	Rate ($/1000 gallons)
0 – 2	$ 1.42
3 – 10	$ 2.02
11 – 15	$ 2.98
16 – 29	$ 3.41
≥ 30	$ 4.08

Results

A set of simulations was completed to analyze the trade-offs for Model 1 and Model 2 when the four adaptive management strategies are enacted separately and in combination. The following results include sets of non-dominated solutions for optimization Models 1 and 2 for the Outdoor Restriction and Reverse Trigger/Target Reduction strategies; sets of non-dominated solutions for the Development Density and

Rainwater Harvesting strategies; and finally, the results for Models 1 and 2 of the Combined Strategy.

Simulation-optimization Settings

Each simulation was performed for a time period of 25 years, for monthly time steps, beginning in 2010 and ending in 2034. A historic climatologic time-series of rainfall and temperatures from 1950 to 1974 was used, which incorporates the drought of record. The initial population is 365,438 residents, divided into 146,175 household agents, which increases according to the projections adopted by the Texas Water Plan (Freese and Nichols et al. 2010).

Each optimization was performed five times, initialized with a different random seed, using a population size of 30 solutions over 50 generations. A crossover rate of 90% and a mutation rate of 1% were adopted (Table 7). For each of the five demand management strategies, the results section shows a representative set of non-dominated solutions from the five trials. For each non-dominated set, the final population of 30 solutions is shown.

Outdoor Restriction and Reverse Triggers/Target Reduction Strategy

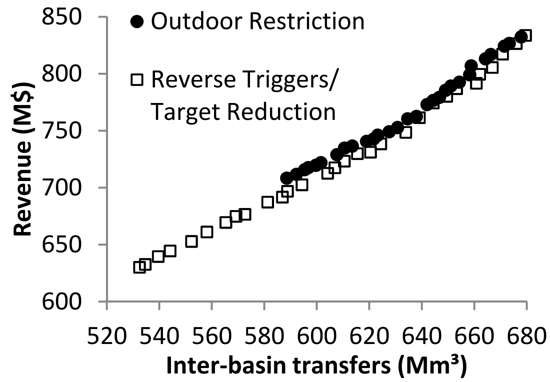
The Outdoor Restriction and the Reverse Triggers/Target Reduction strategies were optimized and two non-dominated sets (Inter-basin transfers versus Revenue, and Inter-basin transfers versus Restriction Frequency) were identified for each Strategy (Figure 19 (a) and (b)). These solutions represent, at one extreme, the outdoor water restriction that is implemented when the reservoir storage is lower than the conservation pool level (where each trigger, t_1, t_2, and t_3, is approximately equal to 1), and at the other extreme of the front, the policy is never implemented (t_1, t_2, $t_3 \cong 0$).

Table 7. Algorithmic Setting of the MOEA.

Algorithmic Parameter	**Setting**
Generations	50
Population Size	30
Crossover Rate	90%
Mutation Rate	1%

Solutions for the Reverse Triggers Strategies are located at the region of the non-dominated front where interbasin transfers are reduced more significantly and the demand reductions are higher, compared to the Outdoor Restriction Strategies. This is because once the system enters a drought stage, it remains in that stage for a longer duration when reverse triggers are applied.

(a)



(b)

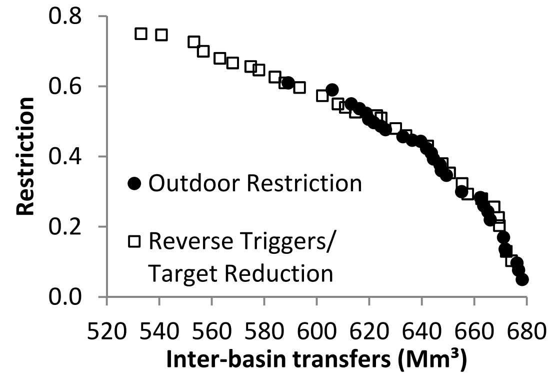


Figure 19. Near Pareto optimal front of inter-basin transfer versus utility revenue (a) and restriction frequency (b).

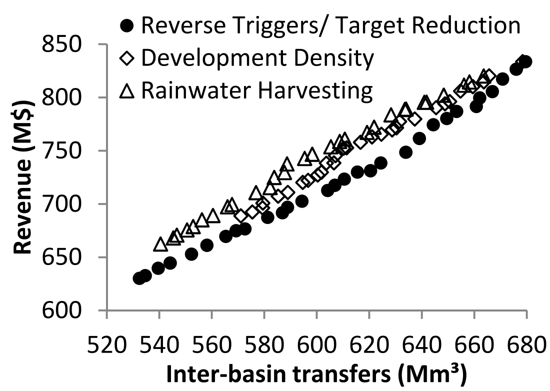
Typically, using reverse triggers reduces inter-basin transfers. In some cases, however, certain combinations of triggers increase inter-basin transfers. For example, the set of triggers {t_1 =0.91, t_2 = 0.80, and t_3 =0.75} is a highly restrictive policy. Using this set of triggers for the Outdoor Restriction Strategy (without reverse triggers), the volume of inter-basin transfers necessary to supply the system is 648 Mm³. The system remains in one of the drought stages for 50% of the simulation period, due to a lower value of trigger 1, and because it remains for a relatively longer time in drought stage 3 (31%). When the reverse triggers are applied for these same settings for the triggers, the time of restriction increases to 60%; however, the time spent in drought stage 3 decreases to 25% of the time, and the volume of inter-basin transfers is 655 Mm^3. Because drought stage 3 is more effective in reducing water use, and its frequency is reduced, the total water use increases and requires a higher inter-basin transfers to meet the demands.

Adaptive Development Density and Rainwater Harvesting Strategies

Strategies that employ outdoor watering restrictions represent short-term policies designed to alleviate drought effects and have little impact on the future water use regime. Both strategies were optimized and the near Pareto front is plotted along with the non-inferior set of the Reverse Triggers/Target Reduction Strategy in Figure 20.

The Development Density and Rainwater Harvesting strategies generate solutions that dominate the solutions identified for the Reverse Triggers/Target Reduction Strategy (Figure 20 (a)). That means that for the same amount of inter-basin transfers, the system is able to generate higher utility revenues. The benefits generated by the Rainwater Harvesting and Development Density strategies enable the system to decrease the frequency of restrictions. This occurs because water savings allow the reservoir to have higher elevations, which decreases the restriction frequency, resulting in higher consumption during wet periods and positively impacting utility revenue. The Pareto-optimal solutions found for the Rainwater Harvesting Strategy result in lower values for the trigger, which controls when drought stages are initiated and ultimately impacts the restriction frequency. For higher values of inter-basin transfers, the Rainwater Harvesting Strategy and the Development Density Strategy solutions have similar performance, but as the restrictions become more aggressive, the Rainwater Harvesting Strategy generates solutions with higher revenue for similar inter-basin transfers, when compared to the Development Density Strategy solutions. Similarly, the Rainwater Harvesting Strategies that are identified for the second set of conflicting objectives (shown in Figure 20 (b)) reduce inter-basin transfers as restriction frequency decreases, more than the Development Density Strategy.

(a)



(b)

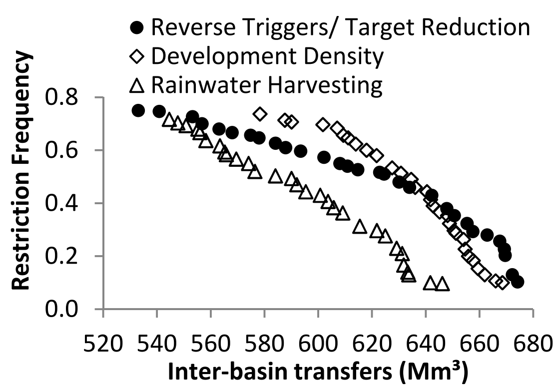


Figure 20. Near Pareto optimal front of Model 1 (a) and Model 2 (b) for the Development Density and Rainwater Harvesting Strategies.

Combined Strategies

Figure 21 shows the non-dominated solutions for the Combined Strategy, which allows implementation of all strategies or a set of strategies simultaneously. The first chart (Figure 21 (a)) depicts the relationship between inter-basin transfers and utility revenue (Model 1). The optimization resulted in solutions with diverse combinations of strategies, depending on the amount of external water resources that can be imported into the system. At one extreme of the Pareto front, one solution does not implement any strategy, which results in the maximum value of inter-basin transfers and revenue. The next three solutions represent the implementation of the Outdoor Restriction Strategy, with increasing levels of the drought triggers. In sequence, the optimization found two solutions that apply the Development Density Strategy, followed by four solutions that implement the Rainwater Harvesting Strategy. The implementation of each strategy separately has limited capacity in reducing water usage, so there is a need to combine two or more strategies in order to reduce inter-basin transfers below 600 Mm^3. The optimization has identified solutions that combine the Development Density and Rainwater Harvesting strategies for the inter-basin transfer range of 600 Mm^3 and 526 Mm^3. For inter-basin transfers lower than 526 Mm^3, the solutions represent a combination of all the strategies.

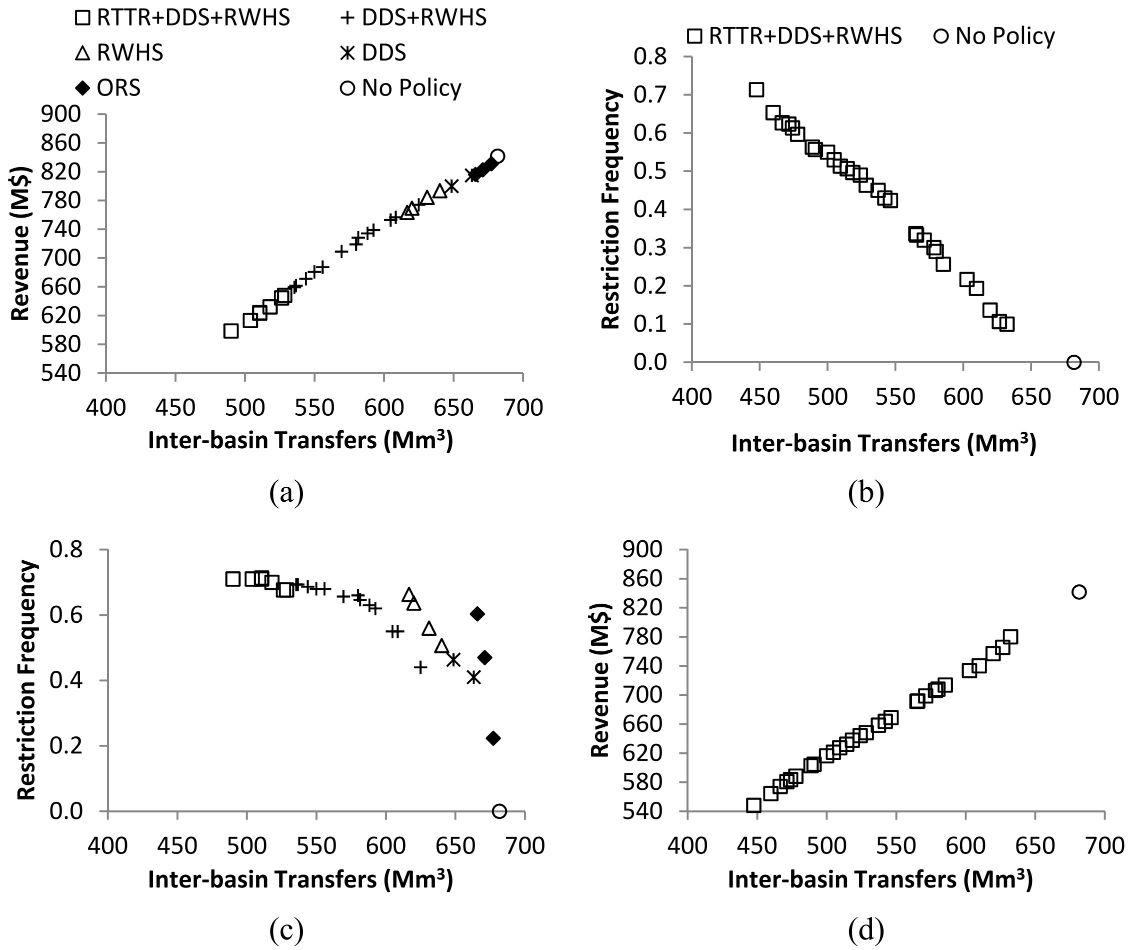


Figure 21. Near Pareto optimal front of the Model 1 (utility revenue) (a) and Model 2 (restriction frequency) (b) for the Combination of Outdoor Restriction Strategy (ORS), Reverse Triggers/Target Reduction Strategy (RTTR), Development Density Strategy (DDS), and Rainwater Harvesting Strategy (RWHS).

The optimization of the second model, the restriction frequency, resulted in solutions that combine all the strategies, with the exception of one solution, which applies no policy (Figure 21 (b)). An analysis of the decision variables of the solutions shows that all the solutions are very similar, with the exception of the trigger values. This result indicates that the reduction of water use for this set of non-dominated solutions is predominately controlled by the level of the drought triggers. All the decision variables were pushed to maximum limits, with the exception of the rainbarrel volumes, which assumed on average approximately 60% of the maximum possible volume.

The non-dominated solutions for the first optimization model (Figure 21 (a)) were analyzed in terms of the objectives for Model 2 (restriction frequency) and plotted in Figure 21 (c). These solutions are suboptimal when compared to the non-dominated set that was optimized for Model 2 (Figure 21 (b)). On the other hand, the solutions found for Model 2 (Figure 21 (b)) were plotted with respect to the objectives used for Model 1 (inter-basin transfers and utility revenue) in Figure 21 (d). These solutions lay on the top of the Pareto front of the utility revenue, indicating that any solution found that minimizes restriction frequency is close to optimal in terms of revenue; however, solutions that maximize revenue are suboptimal in terms of restriction frequency.

Discussion and Conclusions

This research coupled a multi-objective EA with an urban water CAS simulation framework to identify adaptive water demand management strategies and delineate tradeoff relationships between inter-basin transfers, utility revenue, and restriction frequency. Short term strategies (such as the restricting outdoor water use), long term strategies (land use planning and rainwater harvesting system), and their combination were optimized to generate solutions that better cope with the increasing stresses of droughts and population growth.

The results are used here to demonstrate the methodology that can help urban water managers to identify the most effective adaptive management in reducing increasing demands, taking into consideration conflicting trade-offs. The first relationship identified is how a drought contingency plan or a conservation initiative will impact the utilities revenue. The identified Pareto fronts show that the reductions in water consumption and consequently inter-basin transfers linearly impact the utilities revenue in the range of a 25-year period, which can help water managers to plan taking financial consideration in future operations. The second tradeoff is defined by how the reduction in inter-basin transfer impacts the time the water system would be subjected to some water restriction. The results of Outdoor Restriction and Reverse Triggers/Target Reductions strategies show that small decreases of inter-basin transfers result in relative high increases of frequency of restrictions. As the decision maker moves along more restrictive solutions in the Pareto front, higher gains in terms of inter-basin transfers can be achieved by small increments in restriction frequencies. Strategies that enhance supply by rainwater harvesting (Rainwater Harvesting and Combination) shows a more linear behavior between inter-basin transfers and restriction frequency, which means that relative decrease of inter-basin transfer translate in the same incremental increase of restriction frequency, no matter what part of the Pareto front the decision maker is interested.

The results shows that the drought triggers have major impact on the performance of the system, because it defines when and in what degree water restrictions and conservations should be adopted, ultimately defining how the system adapt to changing conditions. For instance, many solutions found values of drought trigger close to each other, indicating the implementation of very narrow drought stages or ultimately the existence of only one restrictive stage. That indicates that existing contingency rules where restrictions measures are implemented incrementally might be suboptimal in terms of the modeled objectives. These solutions mean better efficiency for the physical component of the water system, but might be politically unpalatable.

The combination of all adaptive strategies performs better than any of the tested strategies in separately only when the objective is minimizing inter-basin transfers and restriction frequency. The optimization of utility revenue shows that the best combination of strategies depends on which part of the Pareto front the decision makers are interested. For example, if the system is subjected to a major stress and greater reductions inter-basin transfers are required, than the combination of all strategies is optimal. In another extreme, if only a small reduction of inter-basin transfer is necessary, than the optimal solutions are the ones that applies strategies in separately. Between this two decision regions, there is a compromise region that shows different combinations of strategies.

NSGA-II, as implemented and executed with the settings outlined in Table 7 performed robustly, as the approximate Pareto fronts spread solutions nearly uniformly across the front and included solutions at the extreme ends of the front for all runs. Many solutions found resulted in a very high level of restrictions, which reduces the applicability of these solutions for real systems. For example, many solutions have approximated the values of the drought triggers to one, which reduces the three stage contingency plan to only one drought stage. Such solutions are optimal in reducing inter-basin transfers, maximizing utility revenue, and minimizing the frequency of restrictions, but are likely to be socially inacceptable in many communities. The City Council of Arlington and other municipalities of the Dallas/Fort Worth Metroplex region have been discussing the permanent restriction of outdoor water use to twice a week, which is the same contingency adopted in the drought stage 1. The reality of free and inefficient use of water for outdoor purposes is harder to maintain as the environment and social constraints increase.

The results indicate that short term restriction strategies have limited capacity to reduce the need for external water sources. Long term policies that reduce the pattern of water usage are necessary to improve system sustainability. The present study has explored the impacts of adaptive water demand management in the period of 25 years. Questions remain about the performance of such strategies in longer term periods. Also, only three objectives were analyzed and future work should expand the number of objectives within the water system. Other objectives that can be easily incorporated within the simulation-optimization framework are: environmental inflows for ecosystems protection, costs of operation, maintenance, and expansion of the system, and sustainability metrics (Loucks 1997; Sandoval-Solis et al. 2011).

CHAPTER V

HYDROLOGIC FOOTPRINT RESIDENCE: AN ENVIRONMENTALLY FRIENDLY CRITERIA FOR BEST MANAGEMENT PRACTICES*

The natural hydrologic flow regime is altered by urbanization, which can be mitigated through Best Management Practices (BMPs) or Low Impact Development (LID). Typically, the effectiveness of different management scenarios is tested by comparing post- and pre-development instantaneous peak flows. This approach, however, does not capture the extent of hydrologic change and the impact on downstream communities. A new hydrologic sustainability metric is presented here to quantify the impact of urbanization on downstream water bodies based on the inundation dynamics of the flow regime. The Hydrologic Footprint Residence (HFR) is designed to capture both temporal and spatial hydrological changes to an event-based flow regime by calculating the inundated areas and duration of a flood. The HFR is demonstrated for a hypothetical watershed and a watershed on the Texas A&M University Campus, located in College Station, Texas. For the campus watershed, three design storms (2-, 10- and 100-yr) and a set of historical events (during the period 1978-2009) are simulated for various management scenarios, representing pre-development conditions, development on campus, BMP-based control, and LID-based control. The results indicate that the HFR can better capture alterations to the shape of the hydrograph, compared to the use of the peak flow only.

Introduction

Urbanization alters the natural hydrologic flow regime of receiving water bodies. The transformation of natural cover to roads, rooftops, and parking lots decreases infiltration and increases runoff volumes, while urban storm sewer infrastructure systems change natural stormwater flow paths and increase runoff velocities (Roesner et al. 2001; US EPA 1993; US EPA 2004a; Walsh et al. 2005). As a result, peak flow rates and frequencies may increase significantly in urbanized areas, when compared to pre-development conditions (Roesner et al. 2001). These hydrologic changes cause an increased potential for flooding, erosion, and sedimentation, resulting in damage to property and the loss of in-stream ecosystem health. To mitigate the hydrologic impacts of development, stormwater management in urban areas usually relies on Best Management Practices (BMPs) and Low Impact Development (LID), which are a set of techniques, measures, or structural controls that mitigate the volume of stormwater runoff and improve its quality (US EPA 2004b). BMPs can be classified as non-structural measures, such as public education and street cleaning, or structural measures, such as detention and retention ponds. LID technologies include permeable pavements, rain gardens, rainwater harvesting systems, and green roofs. In general, structural BMPs are synonymous with storage facilities, while LIDs may be classified as infiltration based-facilities (Prince-George's County 2000; Strecker 2001; US EPA 2006). Traditional stormwater guidelines encourage the use of detention structures, and the typical design criterion stipulates that the peak flow passing through a detention pond for a specific rainfall event should not exceed pre-development levels. Designing infrastructure to meet this criterion, however, fails to restore the original flow regime, as excess water that is stored in detention facilities is typically released at a high flow rate for an extended period, when compared to the natural soil storage of pre-development (McCuen 1979). Detention basins that are designed to attenuate flood events will allow small events to pass through unregulated, and consequently, downstream channels are subjected to erosive velocities more frequently than in pre-development conditions (Roesner et al. 2001).

Hydrologic alterations due to urbanization and detention structures invariably impact the ecosystems of receiving water bodies. Minimum flows in rivers and streams are needed to provide a certain level of protection for the aquatic environment, and dramatic shifts in the hydrologic flow regime may damage the physical habitat characteristics by altering the composition, structure, or function of aquatic, riparian, and wetland ecosystems. Historic flow regime parameters can be used as one basis for evaluating the degree of ecological impairment of urbanization. The Tennant method (Tennant 1976) sets a goal for flows based on the historic mean flow. Poff et al. (1997) proposed a methodology to synthesize a set of historic flow parameters, and Richter et al. (1996) formalized the methodology as a set of 32 flow metrics, the Indicators of Hydrologic Alteration (IHA), which characterize statistical properties of a flow regime over a long-term horizon. IHA can be used in conjunction with the Range of Variability Approach (RVA) to measure the change from the natural variability about a central tendency (Richter et al. 1997). Flow duration curves are used to assess changes to in-stream flows by ranking daily flow values and plotting them as a function of their exceedance probabilities (Fan and Li 2004; McCuen and Moglen 1988; US Geological Survey 1992). Other metrics evaluate the erosion potential of streams through calculating the frequency of bankfull discharge, bed load carrying capacity, sediment transport potential, and wetted perimeter (Ackers and Charlton 1970; Booth 1990; Fan and Li 2004; Moglen and McCuen 1988; Whipple and DiLouie 1981). These metrics require additional information about the hydraulics of in-stream flow and the geometry of the channel and floodplain; they are typically more difficult to calculate than those based on historic flows alone. As the complexity of computing and interpreting ecologically-friendly metrics has limited their application in practical stormwater management, a few metrics have been designed to specifically move management towards adopting more comprehensive approaches for evaluating urbanization. Reichold et al. (2010) transformed the set of 32 IHA parameters to a single metric to evaluate land use allocations in watershed development. Nehrke and Roesner (2004) demonstrated the use of the flow duration curve for evaluating BMPs, and Homa et al. (2005) transformed the flow duration curve to one metric, the ecodeficit, which represents the fraction of water no longer available for ecosystem use. Booth et al. (2004) developed new metrics based on continuous data to evaluate the flashiness of a hydrologic regime, and Egderly et al. (2006) used these metrics in combination with event-based metrics for a more holistic approach to watershed development. A few metrics have been developed for assessing LID designs by directly evaluating land use and land cover characteristics, instead of relying on hydraulic and hydrologic calculations (Guo et al. 2010; McCuen 2003).

As LID-based watershed designs are increasingly important to facilitate smart growth of urban areas, a metric for evaluating their benefits is necessary. LID may better mimic the pre-development hydrologic regime and is often considered as a more sustainable practice than BMPs. BMPs typically store and slowly release runoff excess; LIDs enhance infiltration capacity, decrease runoff volumes, and better match the time signature of pre-development rainfall-runoff characteristics (Hood et al. 2007). The peak flow metric does not capture how well a post-development flow regime matches the time signature of the pre-development regime. While the use of metrics based on the long-term flow regime more comprehensively represent the impact of development, they are limited by the need for long records of data and continuous modeling. Event-based metrics can be calculated more readily and are current standard practice for design. Both metrics based on a long-term flow regime and event-based metrics, however, present a suite of parameters that could be difficult for urban planners or land developers to interpret. An event-based metric beyond the peak flow that can be easily calculated and used to clearly communicate the impacts of urbanization on downstream communities is needed to encourage more hydrologically sustainable development strategies that will preserve the natural flow regime. A metric is proposed here that captures both the spatial and temporal dynamics of inundation and can be used to present a more comprehensive perspective of the impacts of urbanization on the natural flow regime. This paper introduces a new hydrologic sustainability metric, the Hydrologic Footprint Residence (HFR) that quantifies the impact of urbanization on downstream water bodies based on the inundation dynamics of the flow regime. The HFR can be used with existing metrics to provide a more comprehensive understanding of the impacts of urbanization on stormwater, as HFR represents flow dynamics that are not captured in the calculation of a peak flow or volume of runoff. HFR requires the collection of additional information regarding channel geomorphology of stream reaches, but may have an advantage over traditional stormwater management metrics as a useful tool for communicating the ideas of watershed management and hydrologic sustainability to lay persons. Similar to the ecological footprint, which represents the amount of land and ocean area that is required to sustain consumption patterns (Rees 1992), the HFR represents the impact of development in terms of acreage, which is a unit that may be more readily conceptualized than existing metrics based on flows or statistical distributions.

Hydrologic Footprint Residence

The HFR associated with a rainfall-runoff event is the area of land that is inundated and the duration over which it is inundated as a storm wave passes through a specified reach of a receiving water body. HFR is expressed in units of area-time, such as acre-hours (ac-hrs). Consider, for example, a rainfall event in a watershed that generates direct runoff and a flood wave as it reaches the receiving water body. The flood wave passing through the reach is represented as a water surface elevation time series and a time series of instantaneous discharge values, or a hydrograph. If proper geomorphologic information of the reach is available, the surface water elevation and corresponding extent of inundated land for a given flow discharge can be calculated at any time using hydrologic models (e.g., the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) (US Army Corps of Engineers 2008)) and hydraulic models (e.g., the Stormwater Management Model (SWMM) (US EPA 2009)). The time series of the inundated area is called the *inundated land curve.* The value of the HFR associated with a storm is calculated by evaluating the definite integral of the inundated land curve, or the area under the inundated land curve.

For example, consider a hypothetical undeveloped watershed, with an area of 1.0 km^2. The cover type is grassland in good hydrologic condition, and for hydrologic soil group C, the corresponding Curve Number (CN) is 74. Other hydrologic parameters for the watershed are listed in Table 8 under the Pre-development Scenario. The watershed outlet discharges to a reach 100 meters in length with channel geometry as depicted in Figure 22 (a). A 1-hr rain event of 55 mm is simulated, and the runoff is calculated using the SCS Runoff Curve Number Method (NRCS 1986). The storm hydrograph is calculated using the Unit Hydrograph Method, and the flood wave that passes through the channel has a peak flow of 7.6 m^3/s (Figure 22 (b)). The time series of the depth of water in the channel (Figure 22 (c)) and the inundated land curve (Figure 22 (d)) are calculated based on the channel geometry. The HFR for this rainfall event is equal to 0.49 ac-hrs.

Similar calculations can be made to evaluate development plans and stormwater control strategies. Residential development in the watershed that changes the land use to ¼-acre lots is represented by modifying the hydrologic model according to the parameters in Table 8, as the Residential Development Scenario. To control any excess surface runoff, a detention pond is designed at the watershed outlet to reduce the peak flow to pre-development levels, described as the Development and BMP Scenario. The pond is designed with a storage capacity of 73,422 m^3 and an outlet structure of three orifices to attenuate the peak flow of the 2-, 10- and 100-yr 24-hr storm events.

The hydrographs and inundated land curves for the Pre-Development, Residential Development, and Development and BMP Scenarios are shown in Figure 23. The peak flow for the Residential Development Scenario increases to 19.0 m^3/s from the Pre-development Scenario peak flow of 7.6 m^3/s, and under the Development and BMP Scenario, the peak flow is reduced to 4.6 m^3/s (Figure 24 (a)). Figure 24 (b) demonstrates that the runoff volume increases approximately 65% due to development of the watershed. The detention pond is able to reduce the peak flow to pre-development levels, but as expected, does not alter the total volume of runoff, as the detention pond stores and slowly releases the excess runoff. The HFR, however, demonstrates different behavior for the Development and BMP Scenario: the HFR is 0.49 ac-hrs, 0.68 ac-hrs, and 0.95 ac-hrs for the Pre-development, the Residential Development, and the Development and BMP Scenarios, respectively (Figure 24 (c)). The additional increase in the value of HFR for the Development and BMP Scenario is due to the change in shape of the hydrograph (Figure 23 (a)), which is caused by the slow release of stored water over an eight-hour period and may indicate that a management strategy that better preserves the original flow regime should be identified. To make the most effective and practical stormwater management decisions, however, a small set of diverse metrics, such as a combination of the peak flow, volume, and HFR, may provide effective and practical guidance for different management objectives.

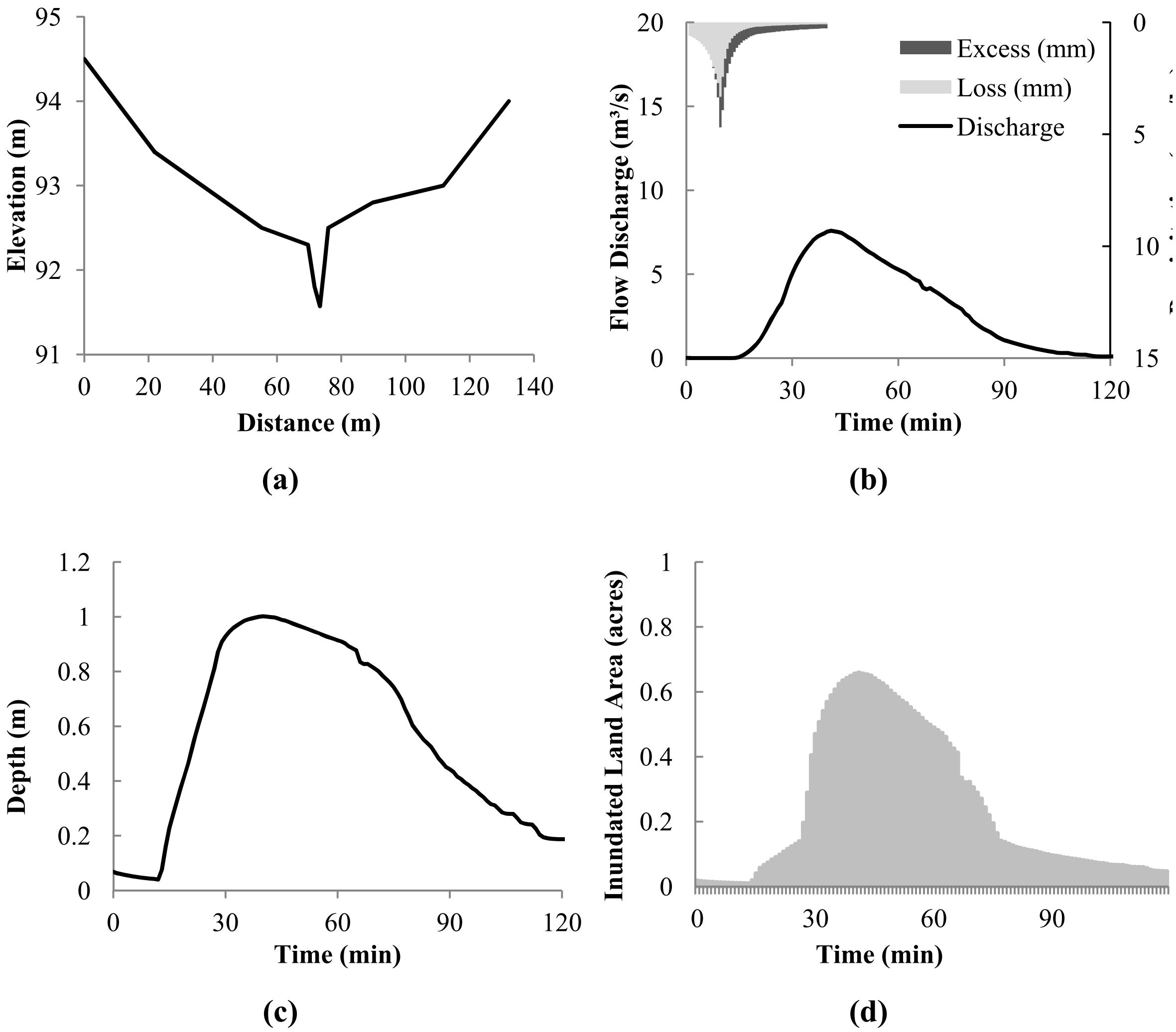


Figure 22. Calculation of HFR for a hypothetical watershed: (a) cross-section of receiving stream reach; (b) storm hydrograph for a 1-hr, 55mm rainfall event; (c) in-stream water surface elevation; and (d) inundated land curve. HFR is the shaded area under the inundated land curve, equal to 0.49 ac-hrs.

Table 8. Watershed characteristics.

Scenario	Time of concentration (min)	Assumed lag time (min)	Impervious Area (%)	CN
Pre-Development	37	20	0	74
Residential Development	16	10	38	83
Development and BMP	16	10	38	83

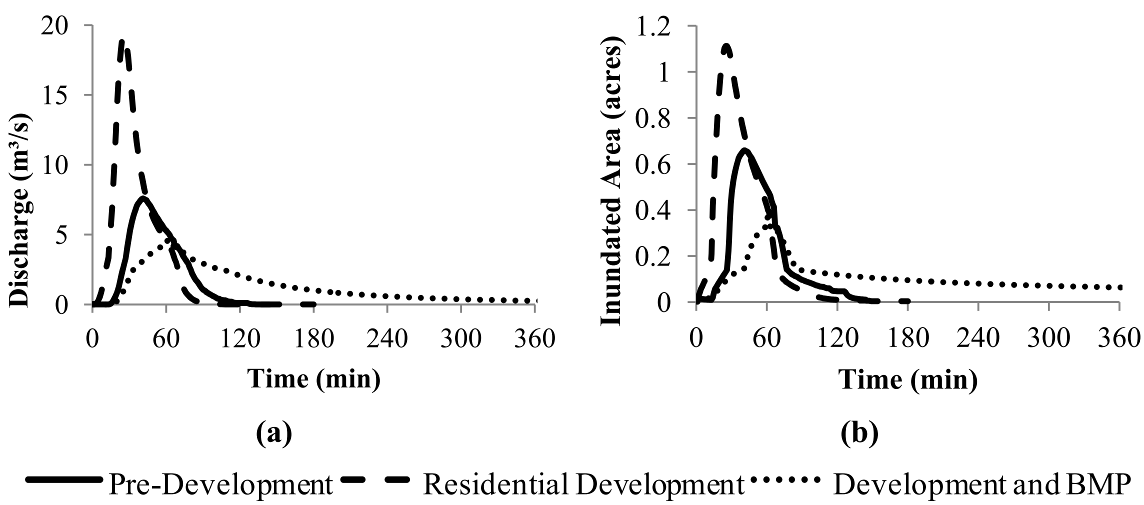


Figure 23. (a) Hydrographs and (b) inundated land curves for Pre-Development, Residential Development and Development and BMP Scenarios.

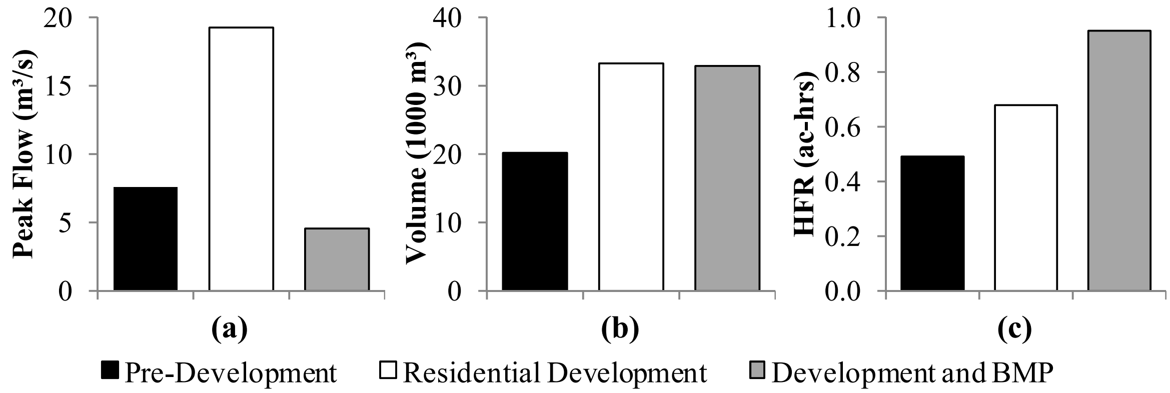


Figure 24. Stormwater metrics for a hypothetic watershed: (a) peak flow (m^3/s), (b) runoff volume (1000 m^3) and (c) HFR (ac-hrs).

Illustrative Case Study

A watershed on the Texas A&M University campus in College Station, TX, is used to demonstrate HFR calculations for a realistic watershed and its use for stormwater management. Watershed D on west campus contributes to tributaries of White Creek, which is in the headwaters of the Brazos River (Figure 25). Tributary D cuts through the West Campus area, draining 3.2 square kilometers through a natural open channel of 2.0 kilometers in length (Figure 26). Soils in this area are clays and sandy clays with sand lens and are classified as Group D hydric soils, and the CN is 77 (City of Bryan/College Station 2008; Thompson 2005). The Upper Subwatershed of the watershed is densely occupied by commercial and university facilities, and the Lower Subwatershed is covered sparsely by urban land use. Due to increased development, erosion and stream bed degradation occurred in Tributary D (Figure 26). Gabions have been placed to alleviate increased velocities, and a detention pond has been recommended for further mitigation of increased stormwater runoff volumes (Thompson 2005).

Hydrologic and hydraulic models of Watershed D are available and have been coupled to simulate in-stream hydrographs (AECOM 2008). The hydrologic component, which transforms rainfall to overland runoff, was implemented using HEC-HMS. The watershed is represented using 245 catchments (Table 9). SWMM serves as the hydraulic modeling component to route runoff through the drainage network, which is represented using 555 channels, composed of round, box, elliptical storm sewers and open channels.

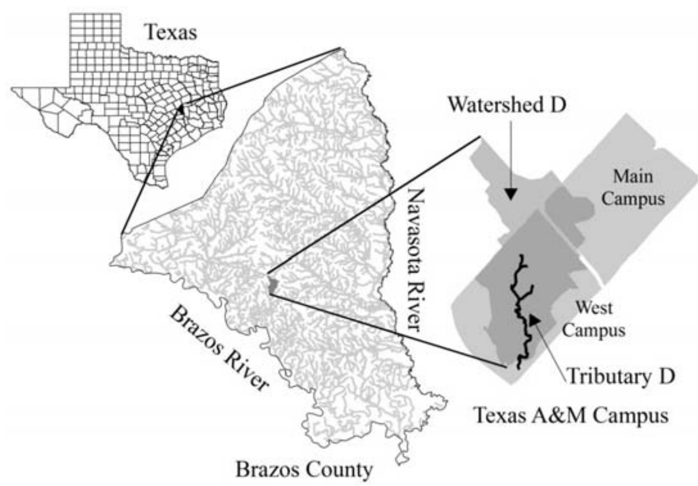


Figure 25. Location of Texas A&M University West Campus and Watershed D.

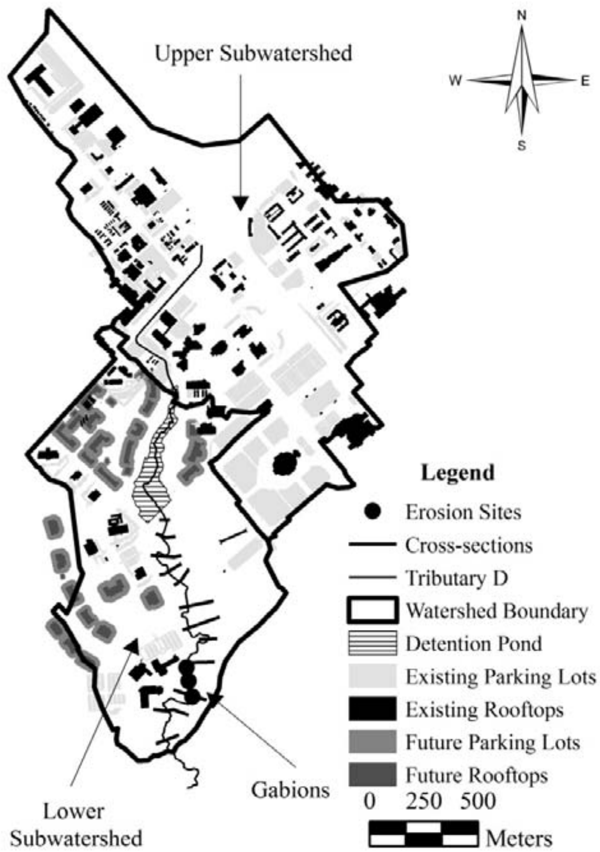


Figure 26. Erosion sites, cross-sections, parking lots, main building rooftops and detention pond in the Upper and Lower Subwatersheds of Watershed D.

Management Scenarios

Four scenarios were modeled to demonstrate the use of HFR for planning purposes: Pre-development, Uncontrolled Development, BMP, and LID Scenarios. Land cover information for each scenario is given in Table 10. Under the existing land use configuration of 46% imperviousness (shown in Table 9), development has caused erosion in Tributary D. Therefore, the Pre-Development Scenario was designed to represent historic conditions when the campus was still developing and could sustain a healthy flow regime, at 23% imperviousness. Under the Uncontrolled Development Scenario, the average percent imperviousness in the entire watershed is 56.1%, and no stormwater control is implemented. The location of new development for this scenario was designed based on the Texas A&M University Master Plan (Texas A&M University et al. 2004), which speculates on the location of future buildings. The ratio of buildings to parking lots for future conditions is based on the existing conditions, where the building area/parking lot area is 0.69. The BMP Scenario was constructed by adding a centralized detention pond to the Uncontrolled Development Scenario (shown in Figure 26). The detention pond has a maximum depth of 5.4 m, volume capacity of 73,372 m^3 and inundated surface area of 46,888 m^2. The outlet structure is a 1m by 1m concrete box and was designed to reduce the peak flow of the 100-yr 24-hr storm by 50%.

The fourth scenario is the LID Scenario. LID technologies for urban areas, such as green roofs, rainwater harvesting, rain gardens, and pervious pavement are simulated to retrofit and replace all rooftops and parking lots that are represented in the Uncontrolled Development Scenario. While there is limited research leading to a representative curve number for LID technologies, Perez-Pedini et al. (2005) represented LID as a simple reduction in CN values of five points. A similar methodology was used by Damodaram et al. (2010a) by reducing CN values by up to 27 points to represent LID strategies that provide various levels of effective storage. In the LID Scenario simulated here, the CN values for all parking lots and building rooftops were reduced by 20 points. Although the Pre-Development and LID Scenarios result in a similar amount of impervious area (23 and 25%, respectively) and the same weighted curve number (82), there are hydrological differences between them. For the Pre-Development Scenario, most of the development is concentrated in the Upper Subwatershed, while for the LID Scenario, similar levels of imperviousness cover the Upper and Lower Subwatersheds (26 and 25%, respectively).

Table 9. Existing characteristics of subwatersheds of Watershed D.

	Impervious Area (%)	Total Area (km^2)	Number of Modeled Catchments
Upper Subwatershed	56.1	1.92	150
Lower Subwatershed	31.1	1.28	95
Total Watershed	46.1	3.20	245

Table 10. Land cover characteristics for four management scenarios.

Scenario	Impervious Area in Upper Subwatershed (%)	Impervious Area in Lower Subwatershed (%)	Total Impervious Area (%)	Area of Parking Lots (%)	Area of Rooftops (%)	Area of LID (%)	Weighted Curve Number
Pre-Development	28	16	23	7	5	0	82
Uncontrolled Development	56	56	56	19	12	0	89
BMP	56	56	56	19	12	0	89
LID	26	25	25	19	12	31	82

Results

Design Storms Events

For each management scenario, the HFR is calculated for three design rainfall events, the 2-, 10- and 100-yr 24-hr storms, with depths of 112.3, 189 and 288.3 mm, respectively (City of Bryan/College Station 2008). Each rainstorm was modeled using the Type III SCS distribution.

To calculate the value for the HFR, the hydrograph and time series of depth of flow were simulated using the HEC-HMS/SWMM modeling framework described above. For each scenario, the HFR was calculated for 11 reaches in Tributary D downstream of the site of the detention pond (Figure 26). For each reach, the HFR is the area under the inundated land curve, and the composite HFR for the total watershed is the sum of the HFR values across the 11 reaches.

The hydrographs for the 2-yr rainfall event (Figure 27 (a)) show that the Uncontrolled Development Scenario generates a peak flow of 30 m^3/s, or 20% higher than the peak flow for the Pre-Development Scenario, which is 25 m^3/s (Figure 28 (a)). The HFR is 39.2 ac-hrs for the Pre-Development Scenario and increases by 14% to 44.5 ac-hrs for the Uncontrolled Scenario (Figure 28 (b)). The use of a detention basin in the BMP Scenario decreases the peak flow below the pre-development level to 22 m^3/s. The discharge is sustained at a higher flow than the other scenarios for approximately five hours after the peak. The inundated land curve for the BMP Scenario shows a correspondingly high inundated area for the same time period, which is reflected in an HFR value, 42.0 ac-hrs, that is 7% higher than the Pre-development Scenario HFR

(Figure 27 (b) and Figure 28(b)). The LID Scenario reduces the peak flow to 26 m³/s, which is higher than the peak flow for the BMP Scenario, but the LID Scenario preserves the shape of the hydrograph closer to the Pre-development Scenario (Figure 27 (a)) and has a HFR value of 40.6 ac-hrs that is 3.6 % higher than the Pre-development Scenario.

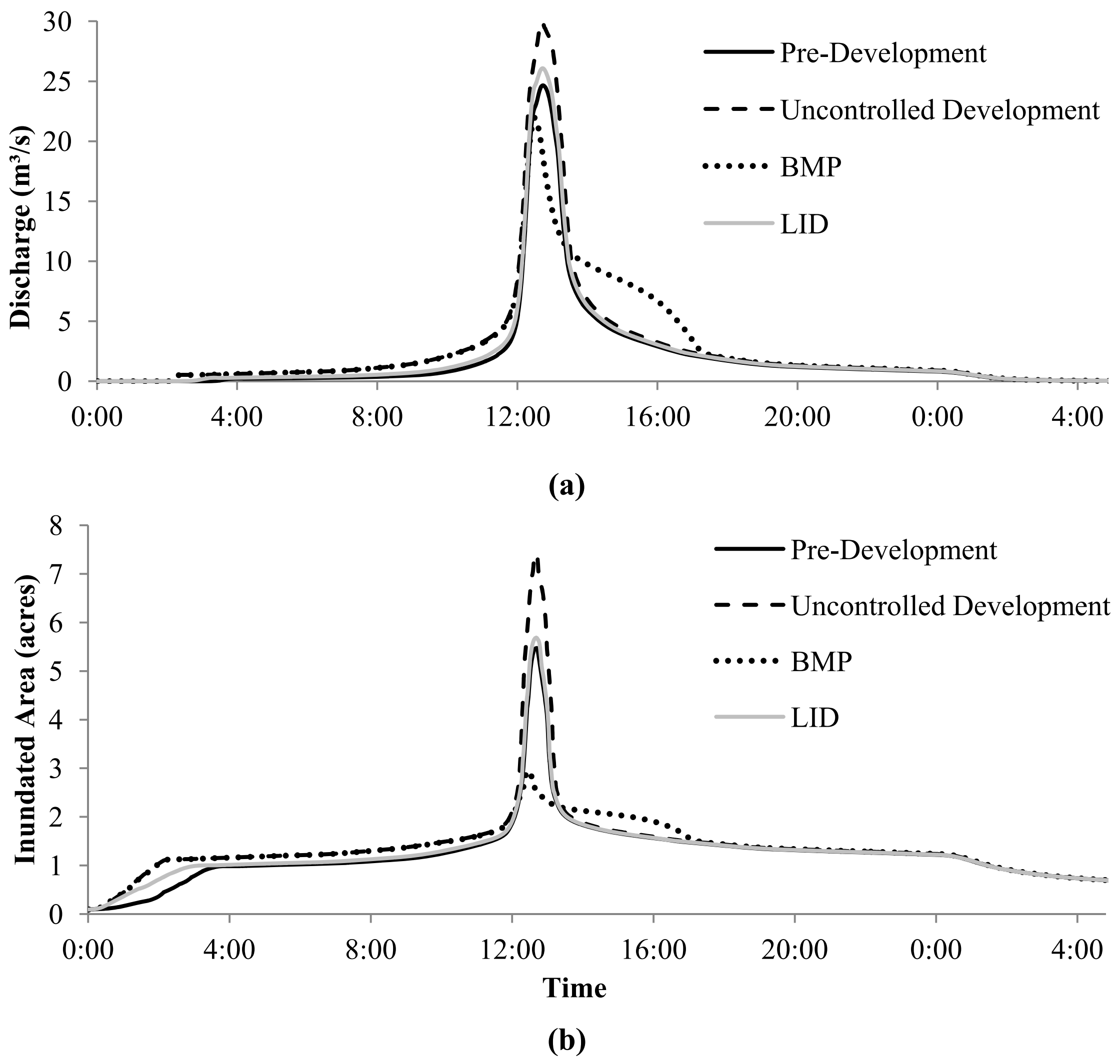


Figure 27. (a) Hydrographs and (b) inundated land curves for the 2-yr rainfall event for the four management scenarios.

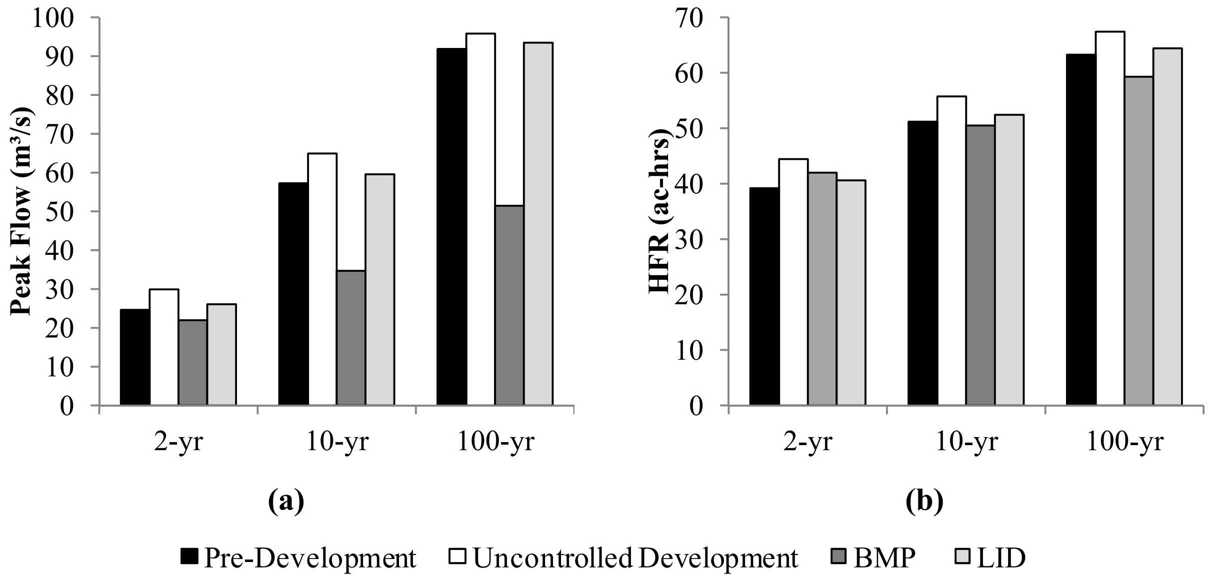


Figure 28. (a) Peak flows and (b) HFR for the three design storms (2-, 10- and 100-yr) for the four management scenarios.

In summary, for the 2-yr rainfall event, the BMP performs better than LID based on the peak flow, but the LID outperforms the BMP when evaluated based on the HFR. For the 10- and 100-yr rainfall events, however, the BMP performs better than LID based on both peak flow and HFR. For the smaller storm, the LID is able to match pre-development conditions more closely than the use of the BMP, due to the increased infiltration capabilities that are simulated through lower CN values. As the depth of the rain event increases, however, the infiltration capabilities are not sufficient to store large volumes of rain, and the BMP is necessary to manage runoff. These results match previously reported studies which document that LID is effective for managing small, frequent runoff events, but performs poorly for mitigating large flood events (Holman-Dodds et al. 2003; Hood et al. 2007).

Sensitivity of HFR to Land Cover Type

Sensitivity analysis was conducted to evaluate the impact of different types of land cover on HFR values. By varying values of the CN for landscaped areas, the diverse infiltration capacities of different land covers are simulated. The CN was varied from its original setting of 77 in increments of 10 units, and HFR values were calculated for the three design storms (Figure 29).

The results demonstrate that the HFR values compare consistently for different land covers. Similar to the base case in which the CN is 77, the LID Scenario generates lower HFR values than the BMP Scenario for the 2-yr rainfall event, but fails to do so for the 10- and 100-yr rainfall events. With increasing CN values, the gain in using LID over BMP is lost even for the 2-yr storm; for a CN of 87, the BMP Scenario performs similar to the LID Scenario for the 2-yr rainfall event and performs better than the LID Scenario to a greater extent for the 10-yr and 100-yr rainfall events. For land covers with high runoff generation, therefore, LID technologies may not have significant impacts, and detention may be a more effective management option.

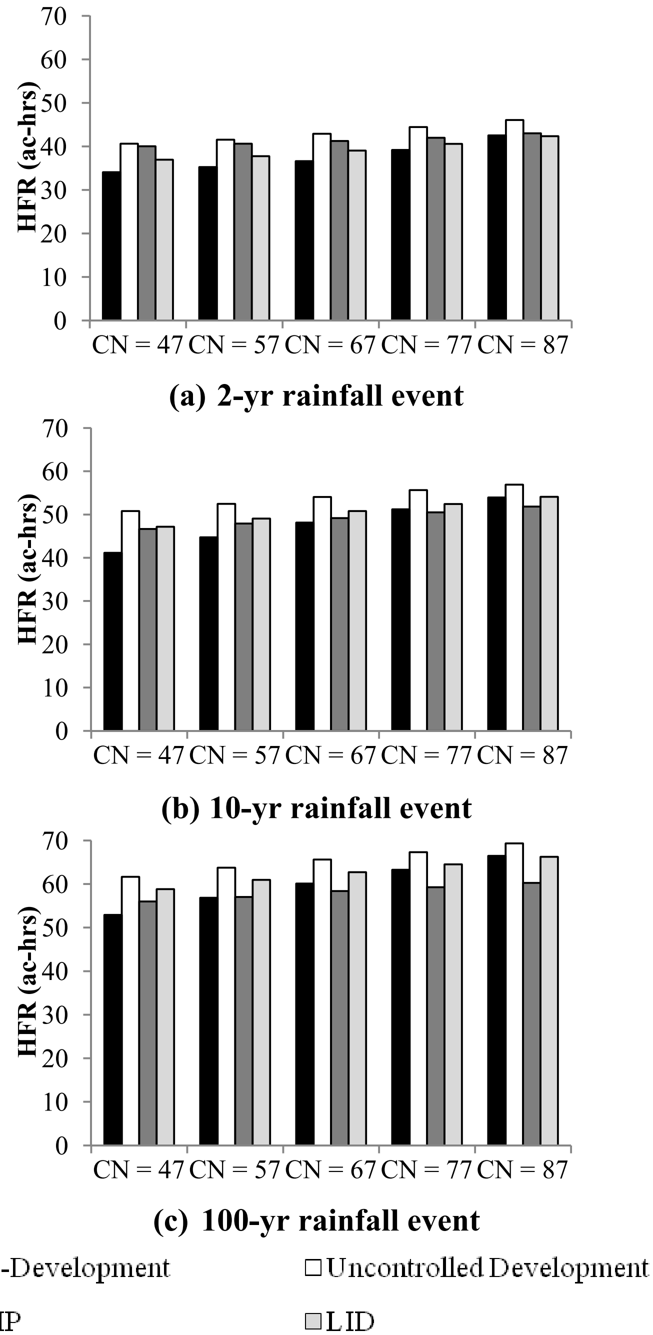


Figure 29. Sensitivity of HFR to different CNs for pervious portions of the watershed. Results are shown for (a) 2-yr rainfall event; (b) 10-yr rainfall event; and (c) 100-yr rainfall event.

Sensitivity of HFR to Length of Reach

As a spatial metric, the HFR incorporates information about the entire length of the reach, which may provide an advantage over flow metrics that are based on data collected at only one location, typically the outlet of a watershed. The user or modeler, however, must make decisions about which reaches should be included in calculating the HFR. Figure 30 shows the cumulative contribution of the reaches to the HFR, beginning at the most downstream reach at the watershed outlet and calculated for the 2-yr rainfall event. The reach that contributes the highest increment to the total HFR value is Reach 3 for each of the four management scenarios. Reach 3 is the site where erosion has undercut the banks of the stream. Seven of the 11 reaches have the same trend that is seen in the cumulative HFR value (Figure 28 (b)), where the order of management scenarios for increasing values of HFR is Pre-Development, LID, BMP, Uncontrolled Development. The LID Scenario has a lower HFR value than the BMP Scenario for all reaches except Reaches 4 and 9. Therefore, the differences among the management scenarios are more significant as more reaches are including in the analysis, and the cumulative impact emerges when the entire reach is considered. As the reaches respond differently to altered flow regimes, different designs for BMP or LID may be identified to target critical reaches in a water body. Further research is needed to explore the impacts of the number of reaches that should be included in the analysis and the potential of using HFR to identify reaches that are vulnerable to erosion.

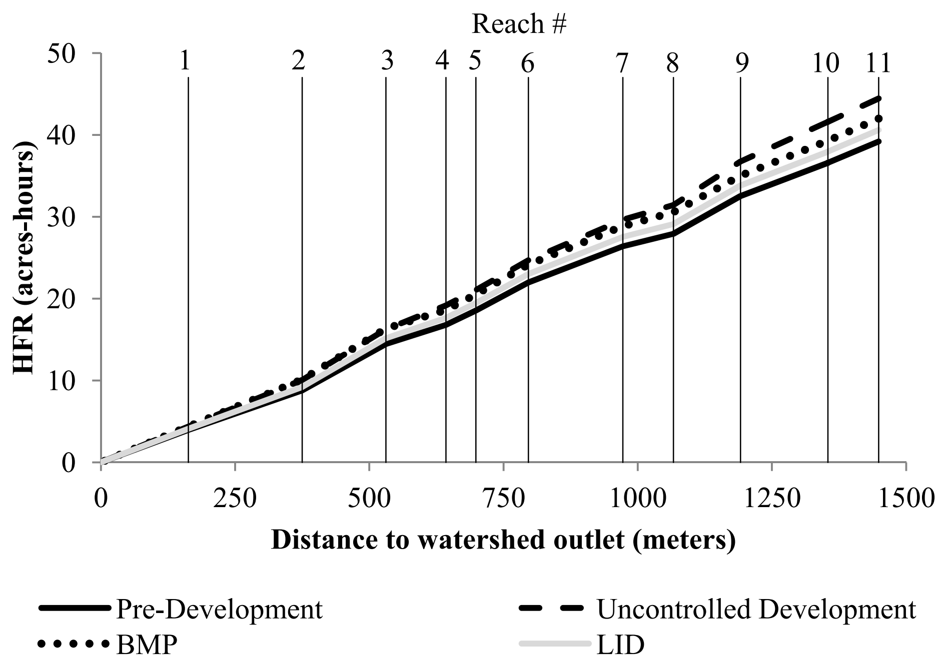


Figure 30. Cumulative HFR for the 2-yr rainfall event from the outlet of the watershed (Reach 1) to the outlet of the pond (Reach 11).

HFR Analysis for Historical Storm Events

HFR values for the four management scenarios were analyzed for a record of historical rainfall events. Thirty-two years of precipitation data from 1978-2009, as reported in 15-minute increments, are available for a rain gauge station located 37 kilometers southeast of the Watershed D (Station COOPID 419491) (NCDC 2009). Station COOPID 419419 is the closest rain gauge station with an historic rainfall record of more than 30 years, and data is reported in sufficiently small time intervals for hydrologic simulation of Watershed D. This rain gauge is considered as representative of the rainfall on campus. During the 32 years of recorded rainfall, 78 events were recorded that generated a depth of rainfall greater than 50.8 mm (2 inches) and were separated by at least four hours (shown in Figure 31). Rainfall depths above 50.8 mm of represent significant events that can be used to evaluate management decisions. The rainfall event that produced the greatest depth of rain occurred in October 1994, with an accumulated depth of more than 388 mm (15.3 in.) of precipitation over 19 hours. The majority of the storms resulted in depths of rainfall that did not exceed the 2-yr design storm.

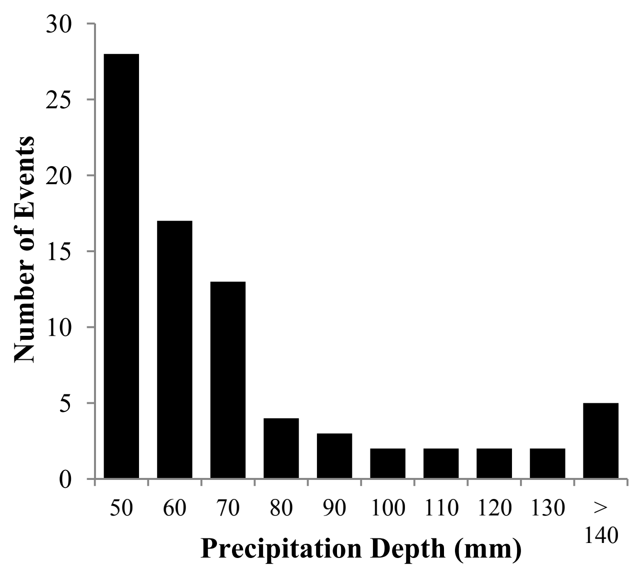


Figure 31. Histogram distribution rainfall depth of 78 historical events, recorded during 1978-2009.

The HEC-HMS/SWMM modeling framework was used to calculate the HFR values for the 78 rainfall events. The cumulative frequency was computed using the Weibull formula (Stedinger et al. 1992) to generate empirical distribution functions of peak flow and HFR for all events (Figure 32). The exceedance probability, which is the probability that a given peak flow or HFR will be exceeded is the cumulative frequency minus one. Because the cumulative frequency was computed for depths that exceed a threshold, and not annual extreme values, the concept of return period or recurrence interval does not apply to the estimated frequencies.

The peak flow curve of cumulative frequencies for the Uncontrolled Development Scenario is shifted to the right when compared to the Pre-Development levels, which indicates an increase in the peak flow for any specific frequency. For cumulative frequencies lower than 0.5, both BMP and LID Scenarios restore the peak flow frequency curves close to pre-development regimes. For peak flows with cumulative frequencies higher than 0.5, the BMP Scenario reduces peak flows below pre-development values, while the LID Scenario brings peak flows below the Uncontrolled Development Scenario, but not to pre-development levels (Figure 32 (a)).

While the peak flow frequency curves for the Uncontrolled Development and BMP Scenarios are significantly different, the HFR frequency curves are similar, with exception of the largest event (Figure 32 (b)). Though the BMP Scenario reduces the peak flow for the majority of the 78 storms, the flow is attenuated in the reach, leading to higher HFR values. This is the same behavior reflected in the analysis of the 2-, 10-, and 100-yr design storms. The LID Scenario more effectively matches the HFR frequency curve of the Pre-Development Scenario for the entire spectrum of analyzed storms.

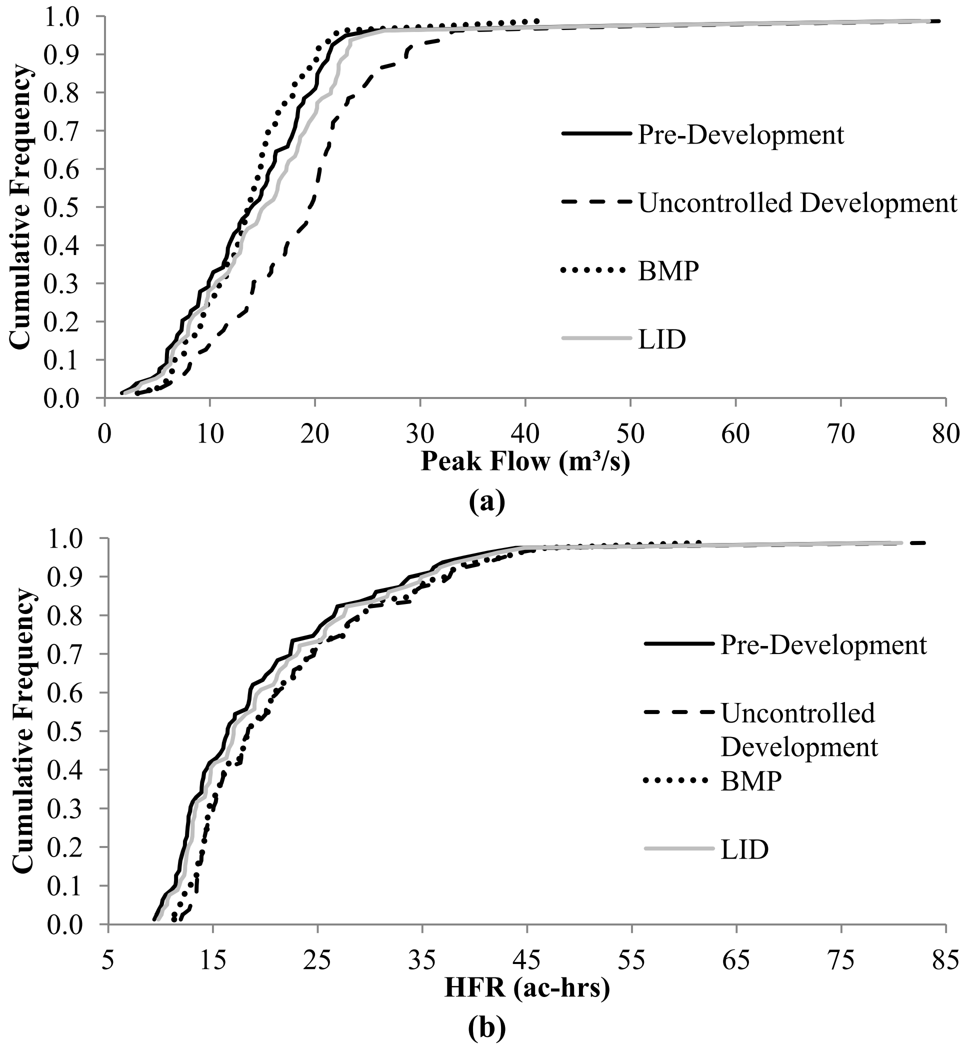


Figure 32. Cumulative frequency of (a) peak flow and (b) HFR.

Discussion and Conclusions

A new metric designed to assess the impacts of urbanization on the hydrological flow regime is described and developed here. The HFR represents the total amount of inundated land area and time of the flood, representing characteristics of both the volume and timing of runoff. Calculation of the HFR was demonstrated for different management scenarios for two case studies, including a hypothetical watershed and an urbanized watershed on the Texas A&M University Campus. The results presented here demonstrated that the HFR can better quantify alterations to the shape of the hydrograph, compared to the use of the peak flow only. For the hypothetical watershed, the value of HFR is increased for a BMP Scenario beyond that of uncontrolled development alone, which may indicate that for some rainfall events, the impairment to the hydrologic flow regime is increased through storage-based stormwater control. For the realistic watershed, HFR was calculated for a 32-yr record of rainfall events and for diverse land cover types for a set of design storms. For this watershed, which is relatively small in area, the difference between HFR values for different management scenarios is a small fraction of the HFR value. When comparing BMP and LID strategies for small storms, BMP results in lower peak flow values, but LID results in lower HFR values, indicating that LID reproduces more closely the shape and magnitude of the pre-development hydrograph. For larger storms and for watersheds with less permeable land cover types, BMP performs better with respect to both peak flow and HFR. It has been shown through experimental and modeling studies that LID is limited in controlling flooding that accompanies less frequent, more intense storms. Given limited budgets, a tradeoff may exist when choosing to implement LID to restore the natural hydrologic flow regime or implement BMP to control flooding. The use of HFR is being explored to provide insight to comprehensively evaluate watershed management plans for both sustainability and flood control issues (Damodaram et al. 2010b).

Further research is needed to test whether the difference among management scenarios would be more significant for larger watersheds and to determine the sensitivity of HFR to various management strategies, given existing uncertainties in watershed response for a range of rainfall events. Additional investigations should establish the number and location of reaches that should be included in the calculation of the watershed-level HFR value. For the campus watershed case study that was explored here, reaches that contributed most significantly to the cumulative HFR value have experienced increased erosion and undercutting of the stream bank. HFR may provide additional insight to stream hydraulics, as it combines information about the shape of the hydrograph and the geometry of the stream and adjacent floodplain. Future research will explore its correlation to other parameters, including erosion potential, and the potential of coupling the HFR with other important watershed health metrics.

Watershed health is impacted by decisions at all levels, including lot, subdivision, and city-wide levels, and a public understanding of the interaction between urbanization and water resources may lead to better acceptance of stormwater taxes, smart growth, and lot-level LID technologies. The use of HFR may facilitate a sense of ownership of both individual and corporate impacts on hydrologic processes and encourage sustainable watershed development. Ongoing research is exploring the use of HFR for communicating ideas about hydrologic sustainability, flooding, and LID to both homeowners and stormwater managers, compared to traditional stormwater metrics.

CHAPTER VI

HYDROLOGIC IMPACT ASSESSMENT OF LAND USE CHANGE USING THE HYDROLOGIC FOOTPRINT RESIDENCE

Urbanization impacts the stormwater regime. Such impacts can be mitigated by Best Management Practices (BMPs) and Low Impact Development (LID). The typical stormwater criteria used to guide mitigation strategies is that post-development peak flow should not exceed pre-development levels. Peak flow does not capture the whole extension of hydrologic changes, which motivated the development of the Hydrologic Footprint Residence (HFR). Also, post-development configuration can be hard to project, especially for medium and bigger watersheds. This study couples a Cellular Automata land use change model with a hydrologic and hydraulic framework to generate spatial projections of future development in the fringe of a rapidly urbanizing metropolitan area and characterize the hydrologic regime, and uses the HFR for assessing the impacts of BMP- and LID-based scenarios. Three design storms (2-, 10-, and 100-year) were used. The results corroborate conclusions found in previous studies that show that for smaller storms, LID solutions are better with respected to HFR; for larger storms, BMPs strategies perform better with respect to HFR and peak flow.

Introduction

Land use change and urbanization impact the hydrologic flow regime (US EPA 1993; US EPA 2004a). The change from natural land cover such as forests, grasslands, and wetlands, to developed areas including roads, rooftops, sidewalks and other impervious surfaces, alters the hydrologic balance. During storm events in urbanized locations, the amount of rainfall transformed into runoff increases in comparison to pre-development levels because of impervious surfaces decrease the area's infiltration capacity (Roesner et al. 2001). Besides the increase of runoff volumes, its timing signature is altered. Water running off over concrete or asphalt surfaces reaches higher flow than it does over vegetated surface due to lower roughness. In addition, drainage infrastructure is designed to collect water from the surface and conduct it to receiving water bodies by drainage pipes and canals that concentrate flow, which increases its velocity.

Many municipalities require that a rise in runoff volume needs to be controlled, which occurs typically by Best Management Practices (BMPs) storage facilities (US EPA 2004b). The typical design criteria of such structures is that post-development peak flow should not exceed pre-development level for a chosen design storm. Storage facilities, such as detention ponds, however, do not restore the pre-development flow regime, as based on a wide set of descriptive characteristics. Storage facilities can reduce peak flows, which protect downstream areas from flooding; however, they are unable to reduce the increased runoff volumes or restore the timing signature of pre-development flow regime. An alternative to stormwater BMPs is Low Impact Development (LID) (US

EPA 2000), which uses technologies such as permeable pavements, rain gardens, rainwater harvesting systems, and green roofs to control an increase in runoff in the source and better mimic a pre-development flow regime.

An important step in developing watershed management plans is the evaluation of designs through the use of an appropriate and accessible metric. Typically, peak flow can be used to identify the reduction in the highest flow values during a design storm. Alternatively, the Hydrologic Footprint Residence (HFR) is a stormwater metric developed to better assess the impact of urbanization in watersheds (Giacomoni et al. 2012). The HFR represents the amount of land and the time a segment of stream and floodplain is inundated during a storm. Using the inundated area and the time allows for a better characterization of the change in the hydrologic flow regime than a typical instantaneous peak flow. In Giacomoni et al. (2012), the HFR was used to assess the impact of pre-existing, uncontrolled development, BMP-based, and LID-based development scenarios for a set of design (2-, 10-, and 100-years recurrence time) and historical storms for a hypothetical watershed (1 km^2) and for a watershed on Texas A&M University campus (3.2 km^2). A sensitivity analysis for land cover types and length of the stream segment was also performed.

Stormwater management plans are elaborated based on projections of the future development and use hydrologic and hydraulic models to assess the impacts of expected change in land use and simulate alternative management that would mitigate such impacts. Future scenarios are generated based on an array of information, such as projections of population and economic growth, land use zonings, among others, and the uncertainties of these projections can be very high, as it is the result of complex socio-economic processes. Land use change models can be used to improve understanding of urbanization processes and applied to generate projections of future location of development. One of the most popular modeling techniques applied for simulating urban development is Cellular Automata (CA) (Wolfram 1983). CA is a dynamic system characterized by a discrete domain of cells array that change state based on simplified interactions among the cell and its neighbors. Giacomoni et al. (2011) developed a CA land use change model, which is one modeling component of a broader Complex Adaptive System (CAS) simulation framework. The model generates future projections of land use at an annual time step from an initial land cover configuration.

The present study couples projections of land use change generated by a CA land use change model with a hydrologic and hydraulic framework, and computes the HFR to assess the impact of future development and alternative BMP and LID management strategies on the stormwater regime. A watershed located at the border of a large metropolitan area and suffers from rapid rates of urbanization is selected as a study case. The methodology of this study is presented in the following two sections that describe the simulation methodology, the land use change model, the hydrologic and hydraulic framework, and the computation of the HFR. After that, the study case is presented. The next section describes the management scenarios that are adopted, followed by the results sections. In the end, a discussion concludes the study, which includes final considerations and recommendations.

Simulation Methodology

The simulation methodology includes four main modeling components: a CA land use change model, a hydrologic model, a hydraulic model, and the HFR computation (Figure 33). The land use change model is used to generate projected land cover information from an initial land cover. Proper rainfall time series and land use cover are used as inputs to a hydrologic model that computes runoff hydrographs. Stream geomorphologic information builds the hydraulic configuration of the stream, and the runoff hydrographs are used as boundary conditions for the routing computation of the wave flood through the stream reach. The hydraulic modeling generates flow, water surface elevation which are integrated with the stream configuration to compute a time series of inundated land area and compute the HFR.

Cellular Automata Land Use Change Model

A CA land use change model was developed as one component of a Complex Adaptive Systems framework, built to simulate dynamic interactions within urban water systems (Giacomoni et al. 2011). The land use change model simulates the sprawl of urban areas by computing the likelihood of an undeveloped cell within a grid to change state to urban. The likelihood (L) is a function of the normalized number of developed neighbor cells($N_{(x,y)}^{t}$), the normalized distance to main roads ($DMR_{(x,y)}$), the normalized distance of minor roads ($DmR_{(x,y)}$), the normalized distance to central areas ($DCa_{(x,y)}$), and a random number ($Rd_{(x,y)}^{t}$). The likelihood, L, is the weighted sum of these factors:

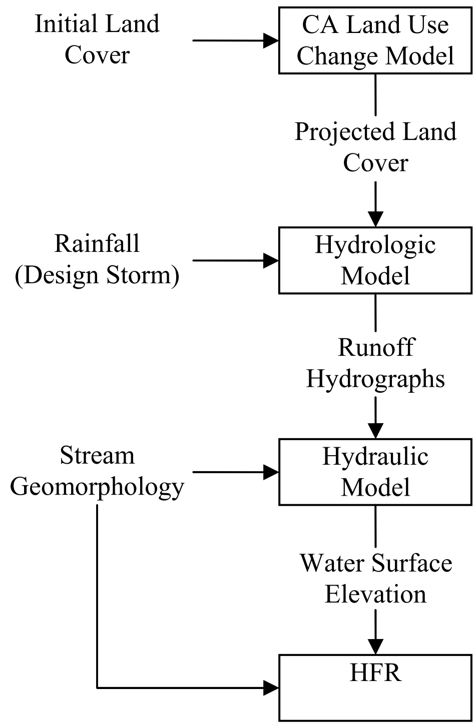


Figure 33. Flow chart of the modeling framework.

$$L_{(x,y)}^{t+1} = \alpha \times N_{(x,y)}^{t} + \beta \times \left(1 - DMR_{(x,y)}\right) + \gamma \times \left(1 - DmR_{(x,y)}\right) + \mu \times \left(1 - DCa\right) + \varepsilon \times Rd_{(x,y)}^{t} \quad (28)$$

$$\alpha + \beta + \gamma + \mu + \varepsilon = 1 \quad (29)$$

where: α, β, γ, μ, and ε are weights; (x, y) indicates the coordinates of the centroid of the cell to serve as a unique identifier; and t is the time step.

The model needs an initial land cover surface in a format of a grid, where each cell can assume only one land cover type. For each annual time step, the likelihood (L) is computed for each cell of the grid and compared to a development threshold function (θ). If the likelihood of a cell is greater or equal than the development threshold function, the cell changes to urban land use. The development threshold function is adjusted to mimic typical urban sprawl pattern, where the development occurs initially in slow rates, accelerating to high rates, and moving toward stability due to the decrease of free and unoccupied land. The development threshold function is a monotonically linear decreasing function dependent of the normalized time ($\hat{t}$) and two parameters (*a* and *b*):

$$\theta\left(\hat{t}\right) = -\left(a - b\right)\hat{t} + a \tag{30}$$

Hydrologic/Hydraulic Framework

A hydrologic model, one used to simulate surface runoff, and a hydraulic package, that routes the surface runoff inside open channels and floodplain, were combined to generate hydrographs, water surface elevations and inundated area for a stream segment, and ultimately used to calculate the HFR. The surface runoff was computed by the model Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998), which is a continuous river basin scale hydrologic model developed to simulate watershed land management practices (Neitsch et al. 2005). SWAT has been used extensively for assessing the effects of land management practices on water quantity and quality, especially in rural environments, and also the impact of land use change from natural and agriculture areas to development (Franczyk and Chang 2009; Miller et al. 2002; Tong et al. 2009). SWAT is a semi-distributed watershed model, where the basin is divided in subwatersheds. Each subwatershed is subdivided in hydrologic response units (HRUs), defined as unique combinations of land cover, soil type, and slope class. For each HRU, the model computes a vertical water balance based on flow of rainfall, evapotranspiration, infiltration, and runoff. SWAT computes the runoff using the SCS Curve Number method. Typically, SWAT runs in a daily time step, which is inaccurate in storm water simulations. However, SWAT also runs in a sub-daily time step and generates flow hydrographs in an hourly time step, which were used as boundary conditions for a hydraulic modeling package.

The model Hydrologic Engineering Center River Analysis System (HEC-RAS) (US Corps of Engineers 2010) is used to perform one-dimension unsteady flow hydraulic analysis of a network of stream segments. HEC-RAS solves subcritical flow calculations and mixed flow regime (subcritical, supercritical, and hydraulic jumps) and performs calculations for cross-sections, bridges, culverts and other hydraulic structures. The output of HEC-RAS is exported to a commercial spread sheet used to compute HFR using the time series of the flow top width and the distances between the cross-sections.

Hydrologic Footprint Residence

The HFR of a specific storm event and segment of stream reach is defined as the area of land that is inundated and the duration over which the flood wave passes through the reach. HFR is a temporal and spatial metric and has units of area and time, such as acre-hours or hectare-hours. As inundated area versus time data is very uncommon to be measured for real events, HFR is typically calculated using hydrologic and hydraulic models for design storms. A hydrologic model that transforms rainfall into runoff hydrographs can be used to generate boundary conditions for a hydraulic model that perform the routing of the flood wave through a stream segment. In the hydraulic component, proper geomorphologic and stormwater infrastructure information, such as cross-sections, bridges, culverts, weirs, or other structures are necessary to compute, at each location along the reach, the flow rate, the water surface elevation, the flow top width, and ultimately the inundate area for each time step. The time series of inundated land cover for the entire reach is called inundated land curve. The definite integral over a time period of the inundated land curve is the HFR. The time period has to be sufficiently long to allow the flood wave to pass through the entire length of the reach.

Illustrative Case Study

The Village Creek watershed (370 km²), located south of Dallas/Fort Worth Metropolitan region (Figure 34) was selected as the study case. Village Creek drains into Lake Arlington (49.6 million of cubic meters that inundated an area of 7.79 km² (TWDB 2008)), which is used as a terminal storage for water supply in City of Arlington. Village Creek watershed suffers from rapid urbanization as the Cities of Arlington, Forth Worth, and other neighboring municipalities face strong economic development and growth.

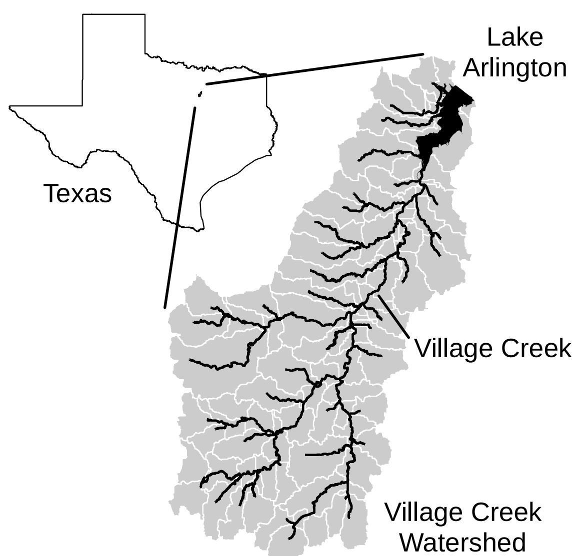


Figure 34. Location of the Village Creek watershed.

Village Creek watershed was divided into 95 subwatersheds (Figure 35) and 469 HRUs that represent unique combinations of five land cove types (urban residential, commercial/transportation, agriculture, forest, and water bodies) and six soil types (with hydrologic classification of B, C and D). Table 11 summaries the areas and percentage of each of land cover type for the year 2010 and 2035. In 2010, urban areas represented approximately 32 percent of the area of the watershed, located mainly in the downstream portion of the watershed around the Lake Arlington (Figure 36). The projected growth of urban development is estimated to double in the 25-year period (2035).

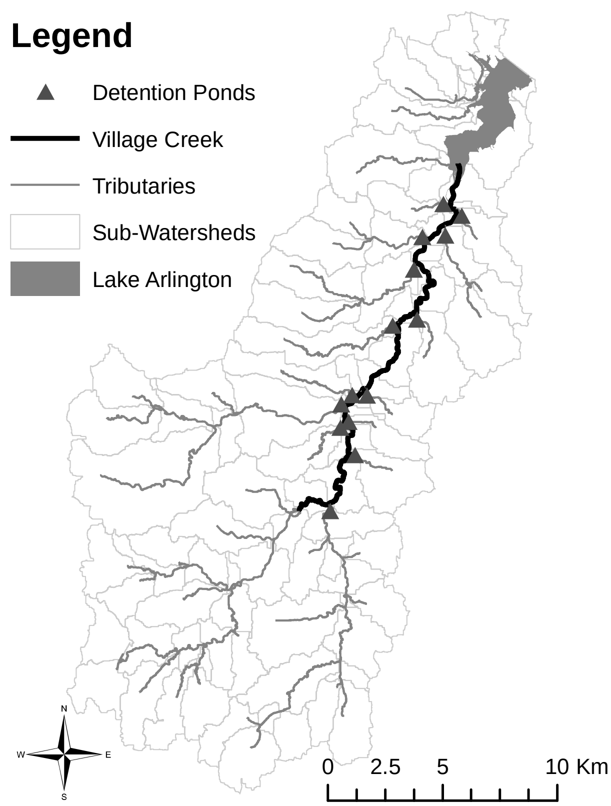


Figure 35.Village Creek watershed, its main tributaries and location of simulated detentions.

Table 11. Land Cover areas and percentages for the years 2010 and 2035.

Land Cover	2010		2035	
	Area (km²)	(%)	Area (km²)	(%)
Water Bodies	7.1	2%	7.1	2%
Urban Residential	104.3	28%	104.3	28%
Urban Commercial	12.7	3%	3.4	3%
New Development	0.0	0%	105.1	28%
Forest	54.4	15%	36.6	10%
Agriculture	191.9	52%	104.6	28%

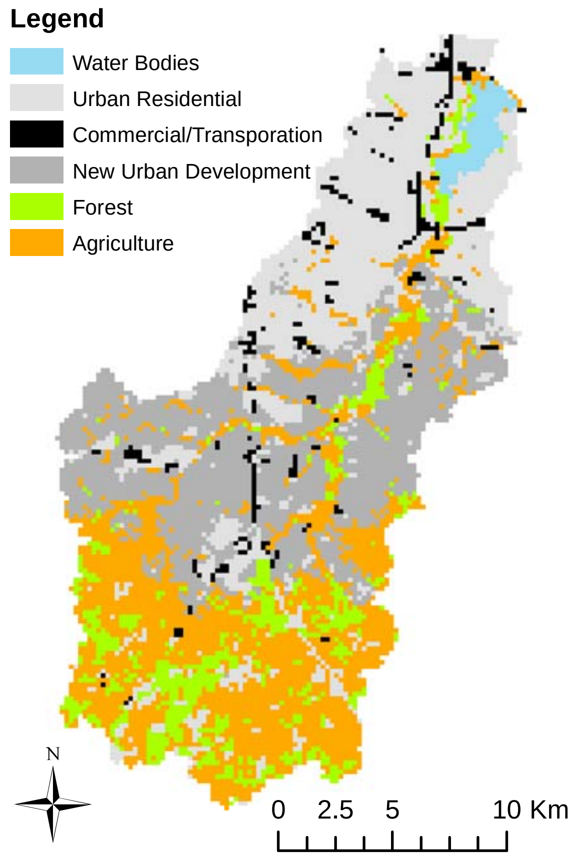


Figure 36. Land Cover of the Village Creek watershed for the years 2010 and the projected new development in 2035.

Simulation Scenarios

The HFR was calculated for four scenarios: Existing Development, Future Development, Future Development/BMP, and Future Development/LID. The scenarios Existing Development and Future Development were built using land cover projections from the CA land use change model for the years 2010 and 2035, which were used as inputs to the hydrologic component. SWAT generated flow hydrographs in five minute intervals that were up scaled to hourly time steps and were used as boundary conditions to the hydraulic routing that was performed by HEC-RAS. A water surface elevation of 550 feet above the sea level is assumed as the boundary condition for the last cross-section, which is the conservation pool elevation for the Lake Arlington. An initial condition of 9.5 cfs is assumed for all cross-sections, which correspond to the flow with 50 percent frequency, according to flow data registered in the USGS 08048970 flow gage at Everman, which is located in the Village Creek. Although Village Creek is represented by 124 cross-sections along a reach of 22.14 km in HEC-RAS, only 96 cross-sections are used in the HFR computation because of the influence of the lake in the most downstream segments of the creek. Figure 35 shows the segment of the Village Creek where hydraulic simulations were performed. Among the 124 cross-sections, there are 11 bridges that cross Village Creek.

The scenario Future/BMP represents a management strategy that controls increasing runoff by the construction of fourteen detention ponds, each one located in the main downstream tributaries of Village Creek (Figure 35). Each of the detention ponds was designed to attenuate the peak flows generated by the 2-, 10-, and 100-years of return period design storms of 2050 to pre-development level (1973). The detention ponds were designed with one of more outlet structures with three orifices, each one to control one of the design storms (Figure 37). Each orifice was designed according to the equations 1 to 3, where *a* and *b* are the width and height of the orifice 1; *c* is the width of orifice 2; *d* and *e* are the width and depth of orifice 3, respectively; h_2, h_{10}, and h_{100} are the maximum depth of water for the 2-, 10-, and 100-year storms; Cd is the dimensionless orifice discharge orifice (assumed equal to 0.6); and K_w is a weir discharge coefficient (assumed equal to 0.4). The number of structures, orifice dimensions, maximum volume, depth and design storms for each detention pond are listed in Table 12. The location of each of the detention pond is shown in Figure 35.

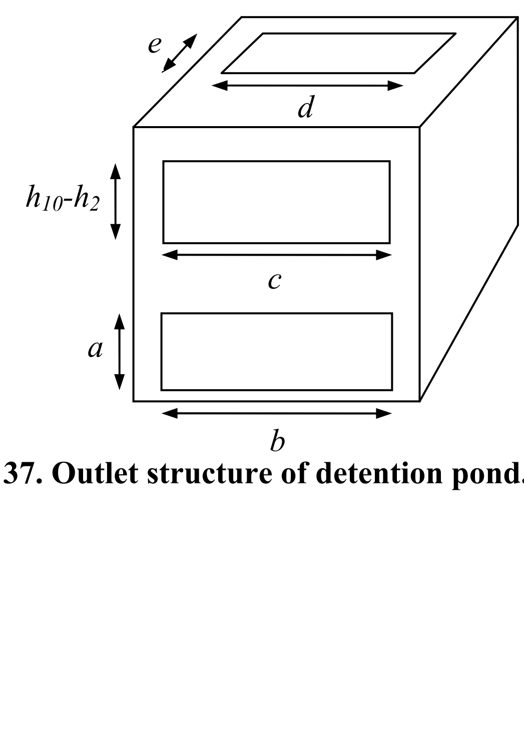


Figure 37. Outlet structure of detention pond.

$$Q_2 = C_d \times a \times b\sqrt{2g\left(h_2 - a/2\right)} \tag{31}$$

$$Q_{10} = K_w\sqrt{2g}C\left(h_{10} - h_2\right)^{1.5} + C_d ab\sqrt{2g\left(h_{10} - a/2\right)} \tag{32}$$

$$Q_{100} = de\sqrt{2g\left(h_{100} - h_{10}\right)} + C_d c\left(h_{10} - h_2\right)\sqrt{2g\left(h_{100} - (h_{10} + h_2)/2\right)} + C_d ab\sqrt{2g(h_{100} - a/2)} \tag{33}$$

Table 12. Detention ponds characteristics.

Pond	Number of Structures	a (ft)	b (ft)	c (ft)	d (ft)	e (ft)	Volume (acre-ft)	Depth (ft)	Q_2 (cfs)	Q_{10} (cfs)	Q_{100} (cfs)
1	2	2.08	9.4	9.4	5.74	1.05	699	10	320	720	1277
2	1	0.93	6.13	6.13	3.44	0.58	105	5	34	78	141
3	1	1.39	7.61	6.03	3.14	0.52	45	4	45	92	153
4	1	0.74	4.57	4.57	2.55	0.43	51	4	18	41	74
5	2	1.91	15.26	10.98	5.29	0.92	556	10	461	970	1637
6	1	1.39	9.21	7.60	3.58	0.60	50	4	55	113	188
7	1	0.79	4.22	4.55	2.62	0.44	52	4	18	41	74
8	1	1.69	8.12	6.32	3.77	0.58	79	5	65	135	225
9	1	1.44	5.33	6.84	3.88	0.62	105	5	42	95	170
10	2	1.33	9.96	7.58	3.99	0.61	160	6	162	333	557
11	1	2.16	18.82	6.40	2.81	2.49	75	4	130	268	447
12	1	1.29	11.05	11.05	4.78	0.85	165	6	90	199	351
13	1	0.76	7.17	7.17	3.13	0.53	52	4	29	65	116
14	1	1.35	5.31	4.91	2.99	0.42	17	4	31	66	111

The last scenario represents a management strategy to control runoff by Low Impact Development (LID). In this scenario, all the new development that occurs from 2010 to 2035 is considered a new type of land cover. Figure 36 shows the location of the new development that occurs from 2010 to 2035. It is assumed that urban parcels have installed rainwater harvesting, green roofs, and pervious pavements, which increases retention and infiltration of stormwater in the source. To simulate the reduction of runoff generation, a Curve Number five units lower is assumed, which is the same value assumed by Perez-Pedini et al. (2005).

Design Storm Events

Each of the scenarios was simulated using as input the 2-, 10- and 100-year design storms, with a duration of 24 hours. Each storm generates a total of 107, 173 and 257 mm of rainfall. It is used a Type III SCS distribution, which has the peak of rainfall intensity in the middle of the total duration (12 hours). The hyetograph of the 2-, 10-, and 100-year storm are plotted in Figure 38.

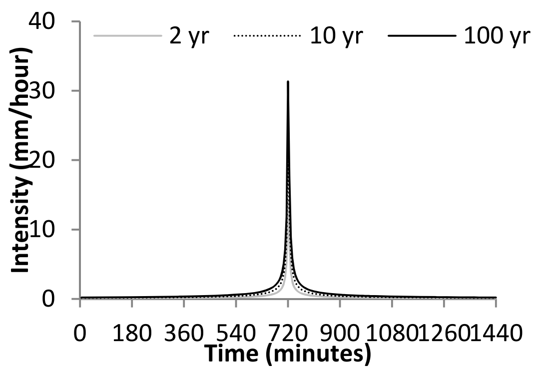


Figure 38. Hyetograph of the 2-, 10-, and 100-year storm for the Tarrant County.

Results

The HFR values for each scenario were computed using the hydrologic and hydraulic modeling SWAT/HEC-RAS framework. HEC-RAS computed the hydrograph, water surface elevation, and top width of water for each cross-section at each time, which was used to computed the inundated areas curves. Figure 39 and Figure 40 show the flow hydrographs and inundated area curves for the 2- (a), 10- (b), and 100-yr (c) storms for the Present, Future, Future/BMP, and Future/LID scenarios.

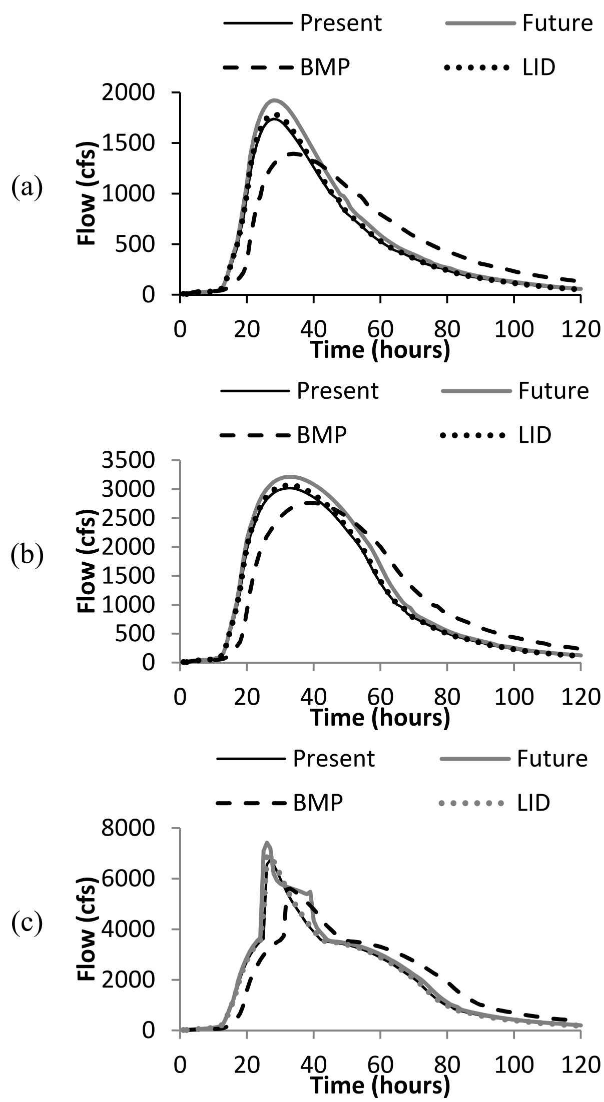


Figure 39. Flow hydrographs for the Present, Future, Future/BMP, and Future/LID scenarios, for the 2-yr (a), 10-yr (b), and 100-yr (c) design storms.

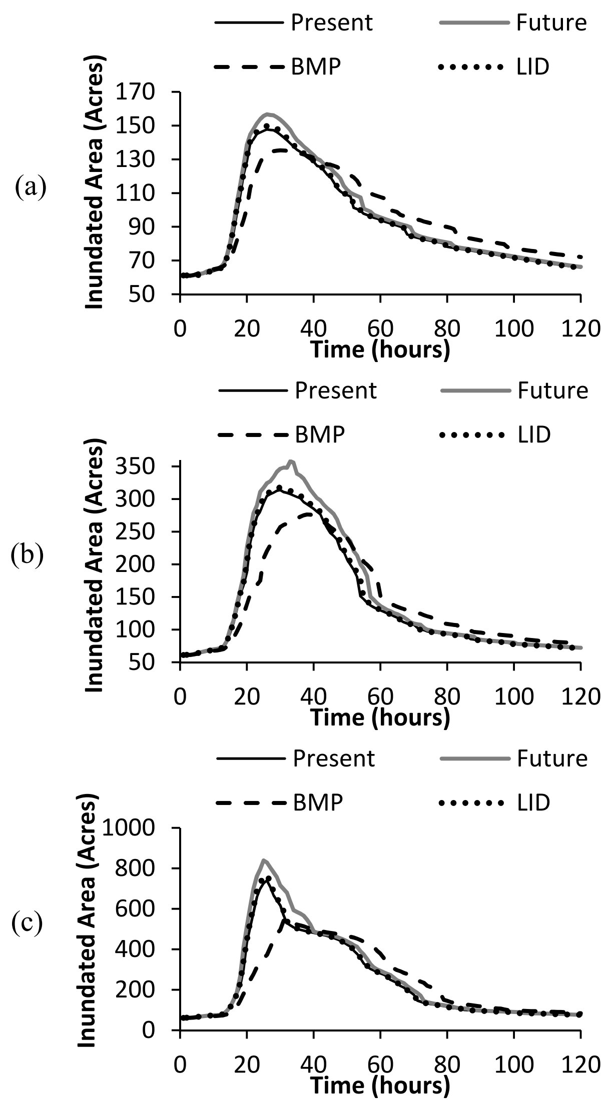


Figure 40. Inundated areas for the Present, Future, Future/BMP, and Future/LID scenarios, for the 2-yr (a), 10-yr (b), and 100-yr (c) design storms.

For the Present Scenario, the peak flow increases by a small amount for the storms of increasing depth (Table 13), and the Future Scenario shows an increase in peak flow compared to the Present Scenario. The Future/BMP scenario decreases the peak flow to lower levels than the Present scenario due to the detention ponds, which are over-designed when evaluated for the year 2035. In addition to reduction of peak flows, as shown in Figure 39, the time of the peak is delayed by several hours, and this change in the hydrograph is not captured by the peak flow metric. The Future/LID Scenario effectively restores the hydrologic regime to 2010, as the shape, timing and peak of the hydrograph are very similar, with a small difference in the peak flow.

Table 13. Peak Flow (cfs) for the 2-, 10-, and 100-year storms for the Present, Future, Future/BMP, and Future/LID scenarios. The percentage values show the difference from the Present scenario.

Scenario	2-yr storm		10-yr storm		100-yr storm	
	Peak Flow (cfs)	Reduction (%)	Peak Flow (cfs)	Reduction (%)	Peak Flow (cfs)	Reduction (%)
Present	1737	-	3019	-	6735	-
Future	1922	10.6%	3213	6.4%	7425	10.2%
Future/BMP	1393	-19.8%	2763	-8.5%	5606	-16.8%
Future/LID	1783	2.6%	3069	1.6%	6904	2.5%

The Scenarios are compared for the 2-yr storm based on the value of the HFR (Table 14). The Future Scenario increases HFR compare to the Present Scenario at percent change values that are similar to the increase in peak flow. The use of BMPs in the watershed reduces peak flow, but results in higher HFR than the Future scenario, because high flows are prolonged as they are released from the detention ponds. Figure 40 (a) shows that the inundated areas of the Future/BMP scenario are higher than the inundated areas of other scenarios from time step 40 until the end of the simulation (time step 120). The use of LID technologies decreases the HFR values to the level of the Present scenarios and approximately matches the hydrograph and the inundated land curve of the 2-year storm (Figure 39(a) and Figure 40 (a)).

Table 14. HFR (acre-hours) for the 2-, 10-, and 100-year storms for the Present, Future, Future/BMP, and Future/LID scenarios. The percentage values represent the difference from the Present scenario.

Scenario	**2-yr storm**		**10-yr storm**		**100-yr storm**	
	HFR (ac-hrs)	**Reduction (%)**	**HFR (ac-hrs)**	**Reduction (%)**	**HFR (ac-hrs)**	**Reduction (%)**
Present	10,580	-	16,435	-	28,257	-
Future	10,913	3.1%	17,766	8.1%	30,979	9.6%
Future/BMP	10,987	3.8%	16,452	0.1%	28,267	0.0%
Future/LID	10,628	0.4%	16,648	1.3%	28,637	1.3%

Comparing the HFR values for the 10- and 100-yr storms does not show the same analysis as comparison for the 2-yr storm. Unlike the 2-yr storm, the Future/BMP Scenario reduces the HFR for the 10- and 100-yr storms more than the Future/LID Scenario. Instead, when the Future/LID and Future/BMP scenarios are compared, the reduction in HFR for the larger storms shows a similar pattern to the reduction in peak flow; however, the degree of improvement in using BMP over LID is smaller when the HFR is used for comparison purposes. Specifically, when the peak flow is used as a metric, the Future/BMP results in an 8.5% decrease and the Future/LID results in a 1.6% increase of peak flow, compared to the Present Scenario. When the HFR is used as a metric, however, the Future/BMP Scenario produces a 0.1% increase, and the

Future/LID results in a 1.3% increase, when compared to the Present Scenario. Using the HFR as a metric to compare the BMP and LID for large storms may lead watershed managers to select BMP, but expect only a small gain in performance, compared to LID.

Discussion and Conclusions

The present study coupled a CA land use change model with a hydrologic and hydraulic modeling framework to assess the impact of urbanization and alternative management mitigation practices by using a new environmentally friendly stormwater metric. Although predictions of future land use can be very uncertain because of the complex dynamics that govern land use change, the proposed methodology has advantages over other future scenario generation methodologies as it uses spatial projections of land development, generated by a model designed to represent the influence of local interactions among infra-structure and the natural landscape on development patterns. Future development of the CA land use change model is required to include changes among other land uses, such as grassland, cropland, and gradations of urban land cover, including low, medium and high density. The CA land use change model can be used as a methodology to generate trends of future scenarios of development, but cannot be relied on for precise prediction of land use. For larger watersheds, complex dynamics arise from interactions between land use and the hydrologic cycle. A semi-distributed hydrologic model and a hydraulic analysis system were coupled to represent the hydrologic regime and HFR was computed to show how future urbanization and alternative stormwater management mitigate or deteriorate the impacts.

The results of this study corroborate the conclusions found in the previous work (Giacomoni et al. 2012). For smaller and more frequent storms, BMP management solutions perform better with respect to the peak flow, but they are outperformed by LID technologies with respect to HFR. For smaller storms, the retention and infiltration enhancements introduced by LIDs are able to better match pre-development hydrologic conditions, but such capabilities are limited during bigger storms, and the HFR captures this match better than using a peak flow metric. These results suggest that the combination of LIDs and BMPs might bring benefits for a wider spectrum of storms, as it can better match the hydrograph for frequent and smaller storms, and provide the necessary flood control during more intense rainfall events.

Although HFR indicates that Future/BMP scenario performs better than the Future/LID scenario for bigger storms, the shape of the hydrograph and the peak flow of the Future/LID scenario is more similar to the Present scenario than the Future/BMP scenario for all storms. For a smaller storm, the Future/BMP scenario is worse than the Future/LID because it changes the timing characteristic of the flow regime, and HFR captures this change. The performance of the LID scenario to replicate the pre-development hydrograph should be further analyzed, as there are two limitations in the current simulation. The LID is simulated as a 5-point reduction in the curve number, which brings impervious areas to a similar curve number value as the pre-development landscape, which is simulated as 82. In a more realistic case, LID may not bring the hydrologic performance of impervious areas to predevelopment levels. More research is required to better represent the hydrologic characteristics of different LID in the watershed scale. Secondly, the specific analyzed scenarios compare land use configurations between 2010 and 2050, but uses a detention pond design which criteria is reducing peak flow of contributing tributaries from 2050 to 1973 levels. If the comparison between HFR and peak flow were performed between 2050 and 1973, than it is expected that the peak flow of a BMP scenario would better match pre-development levels than LID for big storms, because LID is not capable of reducing significantly runoff generation for more intense storms.

The CA land use change model is part of a larger simulation-optimization framework, developed as an integrative modeling tool to support more sustainable management practices. Besides the simulation of land use change, the CAS framework integrates modeling components of housing and population growth, residential water consumption, hydrologic cycle, reservoir operation, and a water policy/authority agent model. The CAS framework has been used to simulate and optimize adaptive water demand management, focused on problems introduced by population growth, droughts and potential water availability decrease caused by climate change. Future research should use the CAS framework to integrate other aspects of sustainability within an urban water system, including stormwater management. In this regard, HFR can be used as a metric to guide stormwater adaptive management strategies. The CAS framework can be used to assess the diffusion of environmentally friendly technologies, such as rainwater harvesting systems, that have benefits in reducing water use consumption and also controlling the excess of stormwater runoff that ultimately impact stream ecosystems.

Future steps of this study will incorporate a pre-development and longer term future development scenarios. The high resolution hydraulic information contained in the hydraulic model of the Village Creek can be used to assess how sensitive the HFR metric is to the quality of geomorphologic information. Additionally, this study case will be used to evaluate how flow constrained structures, such as bridges, influence the flow regime during storm events, and whether HFR can capture this influence. HFR is a metric developed to better assess the impact of urbanization and different management in the stormwater, and ultimately improve stormwater management sustainability. HFR has proven to better capture the change of the hydrograph than instantaneous peak flow by indirectly considering the increase of runoff volume and the change in the time signature of hydrologic regime. The concept of sustainability however, is still not precisely defined and more investigation on how HFR can guide to more sustainable practices is needed. Future research will be conducted to investigate what is the relationship between the HFR and other metrics that assess the heath of instream ecosystems and does HFR can indicate potential segments of stream or catchments that are more vulnerable to the impacts of urbanization.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The main contribution of this dissertation is the development of a new integrative simulation-optimization framework for urban water resource systems analysis that can be used to assess adaptive management for complex water resource problems. The developed framework is based on the modeling paradigm of Complex Adaptive Systems (CAS), where emergent system properties are the result of dynamic interactions among components. The framework addresses limitations of traditional engineering simulation through incorporation of feedback loops within an urban water resource system and through simulating heterogeneous decentralized autonomous decision-makers. The model developments can lend new insights to urban water resources systems, potentially guiding improvements in efficient management and sustainability.

The modeling framework connects a housing and population growth model, a land use change model, a residential water use model, a hydrologic model, a reservoir model, and a policy/decision making agent model, by using System Dynamics, Cellular Automata and Agent-based Modeling. Each model sends and receives information that is used by other modeling components, creating feedback loops that if ignored, may lead to flawed representation of the system. For example, in the first study, the CAS framework was used to demonstrate the influence of dynamic feedback among water and land consumer decision-making, water and land use regulation, population growth and hydrologic processes, and explored the influence of these interactions on water availability.

Population growth can cause the increase of demands beyond what local water supplies can support, and climate change may cause more frequent and severe droughts; in anticipation of these imminent threats, the water resources management paradigm may shift from supply augmentation to water conservation. New management strategies are required to cope with these increasing threats and modeling techniques that can assess the effectiveness of water conservation plans are important tools to guide better decision making. This research proposes adaptive demand management strategies as an effective approach to increase system sustainability, as it dynamically ties the level and frequency of water conservation implementation to a system-level water availability indicator. With this rule, if the system is submitted to a higher degree of stress, caused by a drought, for example, the implementation of water conservation increases, which helps the system to alleviate water shortages. On the other hand, during periods of sufficient water supplies, the implementation of conservation measures is alleviated. Reactive and proactive rules can help water systems to adapt quickly to changing conditions and improve its efficiencies.

This research coupled an Evolutionary Algorithm to the CAS simulation framework to identify optimal adaptive demand management. Multi-objective optimization was performed to characterize tradeoff relationships among confliction objectives within a water system, such as inter-basin transfer, utility revenue, and restriction frequency. Contingencies strategies, such as restrictions during drought periods, and conservation strategies that have future impact on the footprint of water use, such as rainwater harvesting and land use policies, were optimized in separate and in combination. The results provide a set of settings of policies with different efficiencies and consequent impacts into financial, environment and social components of the water system. The results indicate that the definition of drought triggers plays an important role in the performance of the system, as it defines when and in what degree the system should adapt to changing conditions. For example, the obtained solutions indicate that low number of drought stages outperform existing contingency rules where restrictions measures are implemented incrementally. Such finding might bring benefits for the physical component of the water system, but might be politically unpalatable. The optimization results indicate that the combination of short and long term adaptive strategies outperforms all the strategies only for the objective restriction frequency. When the strategies were optimized for utility revenue, the best combination of strategies depends on how much water can be transferred into the system.

A second contribution of this research is the development of a new hydrologic sustainability metric, developed to better quantify the impacts of urbanization on receiving water bodies. The Hydrologic Footprint Residence captures temporal and spatial hydrologic changes of a flood wave passing through a stream segment by computing the inundated area and the duration of a flood. HFR was used to the study of stormwater management scenarios, such as Best Management Practices and Low Impact Development, and the results show that HFR better capture the impacts of urbanization than other instantaneous metrics, such as peak flow.

The development of the simulation-optimization CAS framework opens many possibilities for future research in the environmental and water resources field, and some recommendations are posed as follows. First, new methodologies are required to characterize the interactions that exist among water consumer agents and the environment. Better understanding of not only how much water is consumed, but the socio-economic processes that influences the consumption of water in a household, is necessary. New understanding of these processes can help the development of more efficient water conservation campaigns and drought management plans. Another recommendation is the study of more flexible adaptive management rules. The adaptive demand management strategies adopted by this study establish a fixed number of stages and fixed measures within each stage. New methodologies can explore more adaptive strategies, where the stages definitions and the measures adopted can change over time, according to the changing conditions of the environment. Climatic and hydrologic forecast models can be used to provide guidance about the future environment, and optimization models can be used to generate the new rules that define adaptive management strategies that utilize climate forecasts and projections.

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